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Nitrogenous fertilizers: Global distribution of consumption and associated emissions of nitrous oxide and ammonia

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Abstract. The global distribution of nitrogen input via application of chemical nitrogenous fertilizers to agricultural ecosystems is presented. The suite of 1° (latitude/longitude) resolution data bases includes primary data on fertilizer consumption, as well as supporting data sets defining the distribution and intensity of agriculture associated with fertilizer use. The data were developed from a variety of sources and reflect conditions for the mid-1980s. East Asia, where fertilizer use is increasing at ~10%/year, accounted for ~37% of the total, while North America and western Europe, where fertilizer use is leveling off, accounted for 17% and 14% of global use, respectively. Former centrally planned economies of Europe consumed one fifth of the 1984 total, but rapid increases in the 1980s are slowing, and consumption trends are variable. The most widely used chemical nitrogenous fertilizer is urea which accounted for 40% of the world's total in the mid-1980s. While almost every country consumes urea, ~75% of the large East Asian fertilizer use is supplied by this one fertilizer. Ammonium nitrate, used primarily in the former centrally planned economies of Europe, in West Asia, and in Africa, accounted for about one quarter of global consumption. These data were used to estimate distributions of the annual emission of nitrous oxide (N_2O) and of ammonia (NH_3) associated with the use of fertilizers. Applying published ranges of emission coefficients for fertilizer types in the data base yields a median emission of 0.1 Tg N_2O-N, with lower and upper values of 0.03 and 2.0 Tg N_2O-N in 1984. This equals <1% to ~3% of the total nitrogen applied via commercial fertilizers and represents <1% to 15% of the annual emission of N_2O from terrestrial sources. Assuming that the ~4% annual increase in consumption of nitrogenous fertilizers during the 1980s corresponds to a ~4% rise in the release of N_2O-N, yearly increases in emissions from fertilizer use are <0.01 to 0.08 Tg N_2O-N equal to <1% to 3% of the current growth of atmospheric nitrous oxide. However, since no measurements of fertilizer-derived nitrous oxide emissions are available for agricultural environments in the tropics/subtropics, where ~40% of fertilizer N is consumed and where consumption is increasing rapidly, relative contributions of climatic regions to current and future emissions remain uncertain. Ammonia emission coefficients for simple groups of fertilizer types were applied to derive the global distribution of ammonia volatilization associated with nitrogenous fertilizer consumption. The 1984 total of ~5-7 Tg NH_3-N, about 10-15% of the annual ammonia source, is concentrated overwhelmingly in subtropical Asia owing to the dominant use of urea with high rates of volatilization. However, the paucity of measurements in representative ecological and management environments suggests that the magnitude and distribution of current and future ammonia emission from fertilizers is still poorly known.

1. Introduction

Nitrogen fixed via human activities is currently equal to or greater than that fixed in undisturbed terrestrial ecosystems [*Vitousek and Matson*, 1993; *Galloway et al.*, 1994]. Nitrogen fixation converts unreactive N_2 to reactive N usable by biotic systems. Fertilizer production accounts for about one half of the ~140 Tg N (Tg = 10^{12} g) fixed annually through human activities [*Galloway et al.*, 1994]. Other anthropogenic sources include energy production and cultivation of leguminous (nitrogen-fixing) crops.

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Large-scale consumption of chemical fertilizers began about 4 decades ago. Global consumption grew ~10% annually between 1960 and 1980 [*Sheldrick*, 1987] and increased ~3.5% per year during the 1980s. N fixation and consumption in the form of chemical fertilizers averaged about 70 Tg annually in the decade of the 1980s increasing at an annual rate of ~2.5 Tg N, from 57 Tg N in 1979 to almost 80 Tg N a decade later. Although some developed regions experienced declining growth trends in the latter period, large growth rates continued in developing tropical and subtropical countries supported by increases in production capacity within those countries.

Consumption of nitrogenous fertilizers, followed by redistribution through gaseous emissions from soils, leaching to ground water, and transport to rivers, alters the nitrogen cycle in various ways. Enhanced ammonia and nitrous oxide emissions are among the deleterious effects of N fertilization.

Others include possibly large emissions of NO and NO_2 [e.g., *Williams et al.*, 1992; *Hutchinson et al.*, 1993; *Chameides et al.*, 1994], and nitrate pollution of groundwater [e.g., *Power and Schepers*, 1989; *Strebel et al.*, 1989]. Increased deposition of ammonium to terrestrial ecosystems has been linked to soil acidification and to forest decline [e.g., *Schulze*, 1989], while reduction of species diversity [*Tamm*, 1990] and stimulation of carbon uptake [*Peterson and Melillo*, 1985; *Schindler and Bayley*, 1993] are possible related effects of fertilization.

Nitrous oxide (N_2O) is a trace gas whose concentration in the atmosphere in 1990 was ~310 parts per billion by volume (ppbv) and is increasing at about 0.2-0.3% per year [*Watson et al.*, 1992; *World Meteorological Organization* (WMO), 1992]; causes of the increase are not understood. The radiative forcing of nitrous oxide is, molecule for molecule, ~200 times that of CO_2, and its long lifetime, ~130-150 years, means that its emission history influences the climate system for long periods of time [*Isaksen et al.*, 1992; *Kim and Craig*, 1993]. The total nitrous oxide source is estimated to be ~5-10 Tg N annually [*Davidson*, 1991; *Khalil and Rasmussen*, 1992]; *Watson et al.* [1992] suggest a broader range of 5-16 Tg. Although the magnitude of individual sources is uncertain, emissions from undisturbed soils, particularly in the tropics, appear to dominate [*Matson and Vitousek*, 1987; *Davidson*, 1991; *Khalil and Rasmussen*, 1992; *Watson et al.*, 1992; *Bouwman et al.*, 1993]; other sources include land clearing, biomass burning, fossil fuel combustion, nitrogenous fertilizer use, and oceans [*Prinn et al.*, 1990; *Davidson*, 1991; *Khalil and Rasmussen*, 1992]. Stratospheric photolysis and chemistry destroys ~10-11 Tg N annually [*McElroy and Wofsy*, 1986; *Prinn et al.*, 1990]. The stratospheric sink, combined with the atmospheric increase of 3-4 Tg N per year, indicates a large imbalance in the nitrous oxide budget; calculated sinks exceed estimated sources by ~40%.

Historically, the imbalance was attributed to underestimated strengths and/or unidentified sources [*Watson et al.*, 1992]. However, *Kim and Craig* [1993] recently reported on $^{15}N/^{14}N$ and $^{18}O/^{16}O$ measurements of N_2O from two major tropospheric sources, tropical rainforest soils and subtropical fertilized soils, indicating that the soils' strong ^{15}N and ^{18}O depletions relative to tropospheric N_2O must be balanced by a source of heavy N_2O. A back-mixing flux of stratospheric N_2O, which is enriched in ^{15}N and ^{18}O, was proposed to balance light biogenic sources although further isotopic measurements are necessary to evaluate this mechanism.

Currently the fertilizer source is considered to be small although estimates rely on a suite of field studies with no measurements of emissions from fertilized agricultural soils in the tropics/subtropics where a large fraction of fertilizers are currently consumed and which are undergoing rapid growth rates in consumption. If further isotopic studies confirm a stratospheric source of N_2O, relative contributions of identified sources to current terrestrial emissions will increase.

Ammonia (NH_3) is the major neutralizing agent for atmospheric acids. The larger sources of ammonia include decomposition of animal excreta, release from undisturbed soils and from fertilized agricultural soils, biomass burning, and oceanic fluxes. Atmospheric NH_3 is removed primarily by wet and dry deposition as well as by reaction with acidic sulphates. The latter converts NH_3 to ammonium-containing aerosols deposited by rainfall and dry fallout [*Asman et al.*, 1988; *Erisman et al.*, 1988; *Schlesinger*, 1991; *Langford and Fehsenfeld*, 1992; *Langford et al.*, 1992; *Dentener and Crutzen*, 1994]. Decline of European forests has been linked to excessive nitrogen deposition downwind of sources [*Nihlgård*, 1985; *Schulze*, 1989; *McLeod et al.*, 1990; *Langford and Fehsenfeld*, 1992]. The "hot spot" nature of nitrogen deposition has been noted by *Melillo et al.* [1989] for western Europe, and ground level measurements of atmospheric concentrations of ammonia and ammonium in England show that local sources are strongly reflected in elevated levels of ammonia, while ammonium concentrations are spatially uniform owing to formation during transport [*Allen et al.*, 1988]. Similar results are found in modeling studies carried out over western Europe [*Asman et al.*, 1988; *Dentener and Crutzen*, 1994].

Fertilizers play a role in the global terrestrial source of ammonia, contributing 10-15% of the total ammonia emission estimated at 45-75 Tg N annually [*Warneck*, 1988; *Schlesinger and Hartley*, 1992; *Dentener and Crutzen*, 1994]. Field measurements and estimates of ammonia volatilization following fertilization of temperate agricultural lands range from 1-46% of applied fertilizer N [*Schlesinger and Hartley*, 1992]. In a study of European sources, *Buijsman et al.* [1987] indicate total losses of ~6% of fertilizer N in the form of ammonia. A recent assessment of the global ammonia budget by *Schlesinger and Hartley* [1992] suggests 8 Tg NH_3-N as a conservative estimate for the fertilizer source in the late 1980s indicating that ~10% of applied fertilizer N may be lost as volatile ammonia.

Numerous field and laboratory studies have increased understanding of the processes and conditions governing fertilizer-related N transformations and emissions in agricultural soils [e.g., *Harding et al.*, 1963; *Hutchinson and Mosier*, 1979; *Breitenbeck et al.*, 1980; *Conrad and Seiler*, 1980; *McKenney et al.*, 1980; *Bremner et al.*, 1981; *Mosier and Hutchinson*, 1981; *Mosier et al.*, 1981, 1986; *Armstrong*, 1983; *Conrad et al.*, 1983; *Slemr et al.*, 1984; *Fenn and Hossner*, 1985; *Goodroad and Keeney*, 1985; *McInnes et al.*, 1986; *Freney et al.*, 1989; *Lightner et al.*, 1990]. Nevertheless, large uncertainties in gaseous N emissions from fertilizer use remain, in part due to the scarcity of measurements of N_2O and NH_3 emissions in tropical and subtropical environments and to the lack of information about the climatic, ecological and agricultural environments receiving fertilizer inputs.

Models of N transformations and exchanges that incorporate climatic and ecological features such as precipitation, temperature, vegetation, or soil texture, require that input data sets capture the environmental and ecological settings in which fertilizer is consumed. In addition, 2-D and 3-D atmospheric chemical models, as well as geographically distributed biosphere models, require spatial accuracy in input data. Therefore, for the data described here, considerable effort was devoted to capturing realistically the geographic distribution of cropland and associated fertilizer consumption.

We present global geographic distributions of nitrogenous fertilizer consumption and associated emissions of nitrous oxide and ammonia. Data sets on the distribution of crop areas and agricultural locations receiving fertilizer inputs are discussed in section 2. The distribution of fertilizer N consumption is presented in sections 3.1-3.3; ranges for estimates of nitrous oxide and ammonia emissions based on simple scenarios are discussed in sections 3.4-3.5 to suggest major regional patterns in emissions. Uncertainties and improvements are evaluated in section 4.

2. Data and Methodology

The spatial distribution of nitrogenous fertilizer consumption was derived by integrating several complementary data sources. Information on total nitrogenous fertilizer use by country and, when available, by fertilizer type, was extracted from fertilizer yearbooks published by the United Nations Food and Agriculture Organization (FAO) [*FAO*, 1985, 1990a, 1991]. Area of agricultural land, by country, was derived from FAO's production yearbooks [*FAO*, 1985, 1990b]. The geographic distribution of agricultural locations in which fertilizer is used is based on the land-use data of *Matthews* [1983]. Country statistics on fertilizer and crop area were located within the appropriate political boundaries using a digital data base of countries of the world [*Lerner et al.*, 1988]. For several countries that are extensive in area and/or consume large amounts of fertilizers, subnational data on agricultural areas and fertilizer use were incorporated. Appendix A lists the data sources used to develop the data base.

2.1. Nitrogenous Fertilizer Consumption by Country and Region

The United Nations Food and Agriculture Organization publishes annual fertilizer yearbooks which provide national statistics on fertilizer production, consumption, and trade for all countries that report them. When provided the information, FAO reports the partitioning of fertilizer consumption into individual types. For nitrogenous fertilizers, the following 10 groups are identified by FAO: ammonium sulphate (AS), ammonium nitrate (AN), ammonium sulphate-nitrate (ASN), ammonium phosphate (AP), sodium nitrate (SN), calcium nitrate (CN), calcium cyanamide (CC), urea (U), other nitrogenous fertilizers (ON), and other complex fertilizers (OC).

For the primary fertilizer data set, we used the FAO country statistics on nitrogenous fertilizer consumption, given in nutrient tons (i.e., tons nitrogen) for 1984-1985 from the *1985 FAO Fertilizer Yearbook* [*FAO*, 1986]. (Note that for most fertilizer statistics, including those of FAO, the reporting year is 1 July to 30 June. Therefore, a single fertilizer year straddles two calendar years and is identified using both.) For countries that reported only total N use in 1984 but reported partitioning among types for some other year during the 1980s, the country's use profile for the reported year was applied to the country's 1984 N total [FAO, 1986, 1990b, 1991]. For countries with no information on the use of fertilizer types for any year in the decade, partitioning was estimated from regional use profiles.

To develop the regional profiles, countries were grouped into 10 regions based on geographic, economic, and agricultural similarities. The regions are (1) East Asia, (2) West Asia, (3) former centrally planned economies (CPEs) of Europe, (4) Africa, (5) Europe, (6) Scandinavia, (7) North America, (8) Central America, Mexico, and the Caribbean, (9) South America, and (10) Oceania. Member countries of these regions are similar but not identical to those used by FAO for statistical reporting.

Proportional contributions of fertilizer types to each region's total consumption were calculated using countries that reported partitioning, and were applied to each region's remaining member countries to estimate global and regional consumption levels for fertilizer types. Table B1 (Appendix B) contains information on fertilizer consumption for the 153 countries listed by FAO, usage of individual fertilizer types for the 101 countries reporting such divisions (Table B1, top portion of regional sections), and type usage for the nonreporting countries calculated by applying relevant regional profiles to country's totals (Table B1, bottom portion of regional sections).

Table 1 summarizes 1984 consumption reports of nitrogenous fertilizer use from FAO indicating, for each region, total N use, number of member countries, number of those reporting N consumption by fertilizer type (in parentheses), and percentage of consumed N for which type information is available. About two thirds of the 153 countries reporting nitrogenous fertilizer consumption provided information on partitioning among types. Forty nine of them reported for 1984; another 52 reported partitioning for some other year in the 1980s. About 30% of the fertilizer consumers did not report fertilizer use by type for any year in the 1980s.

Of the total ~71 Tg N consumed via nitrogenous fertilizers in 1984, about 40 Tg (56%) is partitioned into types either from explicit reporting for 1984 or estimated from type information reported for another year in the 1980s. The remaining ~31 Tg (44%) is reported only as total N by country. The two largest regional consumers, East Asia and former CPEs of Europe, account for almost 60% of the total but have relatively low reporting rates of fertilizer usage by type (38% and 14%, respectively). Only total consumption is reported for the largest consumer in each of these regions: China (East Asia) which consumed over 15 Tg N in 1984 and the former Soviet Union (CPEs of Europe) which accounted for ~10 Tg N in that year. Central, North and South America, West Asia, Europe, and Scandinavia all report over 90% of fertilizer N as a function of type.

To reduce uncertainties in fertilizer distribution within several large countries with regionally variable agricultural activities and/or large fertilizer consumption, more detailed information on fertilizer use for political subdivisions and by fertilizer type was acquired when available. This supplemental information was compiled for China, India, Brazil, the United States, and the former Soviet Union (FSU).

For China, which consumed ~20% of the world's fertilizer nitrogen in 1984, FAO reports only total fertilizer N use for the country. The *China Agriculture Yearbook 1985* [*Agricultural Clearing House*, 1985] and *China - A Statistics Survey in 1985* [*State Statistical Bureau*, 1985] give 1984 provincial statistics on total fertilizer N use. Consumption by FAO types is not available from any of these sources. Therefore the East Asian regional consumption profile

Table 1. Reporting of Fertilizer Consumption by Type

	Region	Number of Countries		Consumption, 10^9 g N	Percent N by Type
1	East Asia	21	(12)	26,017	38
2	West Asia	16	(11)	1,879	94
3	Former CPEs of Europe	8	(3)	14,941	13
4	Africa	45	(30) *	1,848	52
5	Europe	15	(14)	9,562	95
6	Scandinavia	5	(5)	985	100
7	North America	2	(2)	11,691	100
8	Central America/Mexico/Caribbean	22	(11)	1,768	91
9	South America	13	(11)	1,443	100
10	Oceania	6	(2)	371	14
	Total	153	(101)	70,505	55

Shown for regions are number of member countries, number of those countries reporting nitrogenous fertilizer partitioning (in parentheses), 1984-1985 total fertilizer N consumption, and percentage of regionally consumed N reported by fertilizer type. CPE is centrally planned economy.

* South Africa was not used to calculate Africa's fertilizer profile because it is not representative of African consumption patterns.

(Region 1, Appendix B) was applied in each province of China to derive provincial and country use by fertilizer type.

India accounted for almost 10% of the world's 1984 fertilizer N use. FAO reports the country's N consumption of individual fertilizer types (Appendix B, Region 1). *The Fertiliser Association of India* [1989] gives 1988-1989 total nitrogenous fertilizer use for individual states in the same units as FAO (tons nitrogen) but does not identify specific types. The latter source also provides states' consumption of fertilizer types in material tons (bulk weight of fertilizer material), convertible to tons N using accompanying information on percent nitrogen content, by weight, of the various fertilizers. Types distinguished in the Indian fertilizer statistics include ammonium sulphate (20.6% N), calcium ammonium nitrate (25% N), ammonium chloride (25% N), diammonium phosphate (18% N), ammonium phosphate (16% N), ammonium phosphate sulphate (20% N), nitrophosphates (20.7% and 15% N), and several multiple nutrient fertilizers with nitrogen contents ranging from 10% to 28%. These are generally comparable to FAO types. Statistics on state consumption of fertilizer types in material tons were converted to tons nitrogen, and consistency checks were done in two ways. (1) For comparison with FAO reports of country N usage by type, N contents of fertilizer types were summed over the states. (2) State N totals, calculated by converting material tons to tons N and summing over fertilizer types, were compared to reported state N totals from the same source. The small discrepancies uncovered between the several sets of values were traced to typographical errors in the published sources and incomplete reporting of fertilizer use by type for states. Overall, the totals were consistent with FAO so all values were normalized to the FAO country total for 1984.

Although Brazil consumed only ~1 Tg fertilizer N in 1984 and reported by fertilizer type, we constructed information on N use by state because consumption is known to be concentrated in a few areas. Since we were unable to locate statistics on fertilizer N use for states, distributions were calculated indirectly in the following way. From *Brazil: A Review of Agricultural Policies* [*World Bank*, 1979], we obtained national statistics on proportions of total fertilizer N used on individual crops; this information was generally corroborated by *Martinez* [1990] who gives fertilizer N tonnage devoted to major crops grown in Brazil in 1987. State areas of these major crops were derived from *Instituto Brasileiro de Geografia e Estatistica* [1989] for 1987. Since 40% of Brazil's fertilizer N is used on planted pastures, state areas of planted pasture were estimated from *Instituto Brasileiro de Geografia e Estatistica* [1979]. State consumption of fertilizer N was calculated by assuming that a state's use of fertilizer N for a crop is proportional to the state's share of the country's area of that crop. This assumes that fertilizer N application, per unit area, is constant for a crop wherever it is grown in Brazil, and that Brazil's use of fertilizer types, reported for the country by FAO, applies in every state.

For the United States, which accounts for about 15% of global N consumption via nitrogenous fertilizers, more than 80% of FAO's consumption figure for 1984 is listed under the general group "other nitrogen fertilizers" because most of the U.S. consumption is in the form of less commonly used types such as anhydrous ammonia and nitrogen solutions. In order to improve information on the geographic distribution of fertilizer nitrogen throughout the United States, we consulted publications of the U. S. Department of Agriculture (USDA), The Fertilizer Institute, and the International Fertilizer Development Center (IFDC). The USDA gives consumption of selected nitrogenous fertilizers for states of the United States [*Vrooman*, 1987]. These values were converted from material short tons (1 material short ton = 909 kg bulk fertilizer material) to nutrient metric tons (1 nutrient metric ton = 1000 kg nitrogen) by assigning N contents to each fertilizer using information from *USDA* [1985], *Hargett and Berry* [1986] and *The Fertilizer Institute* [1982]. For some fertilizers such as ammonium sulphate, nitrogen contents are standard (e.g., 21% N). Others, such as diammonium phosphate, consist of numerous grades with variable nitrogen contents. Grades in these groups are identified by their fractional N-P-K (nitrogen-phosphorous-potassium) content by weight (e.g., 18-46-0). However, these grades are grouped in this source to include a range of N contents. In these cases, we used the mean N content of the grouped fertilizers to estimate total N for the types. As with India, there are small discrepancies between the fertilizer-type N values calculated from state data and the fertilizer-type N values reported for the country by FAO. These are due to corrections made to earlier years' data in subsequent editions of publications, as well as to incompatible grouping of fertilizer types for reporting purposes, incomplete reporting, and estimated values for N content of combined grades of fertilizers. Total U. S. values calculated from state statistics were normalized to the FAO country total for 1984.

FAO reports only total fertilizer N use for the former Soviet Union which consumed almost 15% of the world's total in 1984. We obtained information on total nitrogenous fertilizer use for the former republics from the Joint Publications and Research Service's (JPRS) statistics handbook on Soviet agriculture [*JPRS*, 1989]. Since no information was available about the use of individual fertilizer types in the former republics, the consumption profile of former CPEs of Europe (Region 3, Appendix B) was applied to each republic to partition fertilizer N by type within the borders of the FSU.

2.2. Locations and Areas of Fertilizer Input

According to global statistics from FAO, 71,000 x 10^6 kg of fertilizer N applied to ~1500 x 10^6 ha of cropland yields a global mean application rate of ~47 kg N/ha for these agricultural lands. Using the distribution of FAO cropland among countries, and assuming that all croplands receive equal inputs of fertilizer N, gives a constant application rate for crop areas within a country or subdivision.

We recognize that fertilizer inputs are not ubiquitous nor are they constant over agricultural lands; they are concentrated in particular crops and vary by country and sometimes from field to field. For example, for 1987, *Martinez* [1990] reports that Turkey used 151 kg fertilizer N/ha on rice and 164 kg N/ha on tea, while Japan used 101 kg N/ha on rice and 578 kg N/ha on tea. It is common for large fractions of commercial fertilizer to be used on export or industrial crops such as tea, sugarcane, cotton, fruits, and vegetables; potato, rice, and maize may also receive heavy applications.

These examples illustrate the difficulty of characterizing geographic variations of fertilizer N inputs on a global basis. Capturing variations among grid cells within a single country or subdivision requires information on areas and locations of individual crops and their fertilizer application rates at fine spatial resolution. Although some information exists about the fraction of crop areas receiving fertilizer in various countries [e.g., *Martinez and Diamond*, 1982], it is available only for selected crops. Furthermore, we do not have precise information on the spatial distribution of crop areas within countries or subdivisions. Therefore, our first goal was to merge the fertilizer statistics developed for regional, national, and subnational units with distributions of FAO crop areas and agricultural locations. We assume that fertilizer N is applied to all crops exclusive of pastures and that inputs are constant throughout cropland within a political unit.

***2.2.1.* Distribution of crop areas.** FAO was the primary source for country totals of crop areas. The FAO definition of cropland includes areas of permanent crops (e.g., tea, tree crops) and arable land (e.g., temporary crops such as wheat); pastures are not included. FAO notes that land cropped multiple times in a year is counted only once; this is sometimes referred to as sown or net cropped area. Although this is the case for most countries, we discovered that identical areas for India were reported as (net) cropland area by FAO and as gross cropped area by *Fertiliser Association of India* [1989]. It is impossible to evaluate rigorously the extent or effect of such reporting inconsistencies, although we confirmed that areas were comparable with FAO when we used national data sources. Inconsistencies may be more common for countries that engage in multiple cropping; that is, where gross cropped area is significantly larger than net cropped area. In addition, errors may occur where pastures are planted and fertilized, but reported by FAO under the general pasture category.

For several large countries, crop areas for subdivisions were needed to reduce uncertainties in the geography. This supplemental information was obtained for India, China, the United States, the former Soviet Union, and Brazil. When these subnational data were available for a year other than 1984, the country totals were normalized to the 1984 FAO cropland total and values for the subdivisions were recalculated by scaling to the country total.

Crop area for the states of India for 1985-1986 was obtained from *Fertiliser Statistics 1988-89* [*Fertiliser Association of India*, 1989]. Sown area for the provinces of China in 1988 was available from the *China Agriculture Yearbook 1989* [*Agricultural Clearing House*, 1989]. Planted area for republics of the former Soviet Union for 1987-1988 was extracted from *JPRS* [1989]. Crop area for the states of the United States for 1982 was obtained from *Agricultural Statistics 1984* [*USDA*, 1984]. Information on crop areas and planted pastures for the states of Brazil was compiled from *Instituto Brasileiro de Geografia e Estatistica* [1979, 1989]; planted pastures were included for Brazil because a large fraction of fertilizer use is devoted to planted pastures.

2.2.2. Distribution of agricultural locations. Crop areas were located into appropriate political units using the 1° digital data base of countries of the world (including the subdivisions for China, India, United States, Brazil and the former Soviet Union). A full discussion of the country data base is given by *Lerner et al.* [1988].

Initially, total FAO crop areas were distributed among all agricultural cells within each political unit. Agricultural cells were identified from the 1° resolution land-use data base of

Matthews [1983], which distinguishes 119 land-use types globally using a hierarchical classification system. Classification criteria emphasize variations in the intensity of agricultural systems and allow for inclusion of crop combinations where information is available. Agricultural locations for the current study were defined initially as all cells identified with cropping activities; that is, grazing cells were not included nor were cells associated with commercial lumbering or no use. Since the *Matthews* [1983] data base was designed to reflect global distributions of agricultural systems, it is useful as a primary guide for agricultural locations but is not precise enough to estimate areas of individual crops or of agricultural land receiving fertilizer inputs.

The method requires that the area of agricultural locations in a country is large enough to accommodate the country's crop area as reported by FAO. For countries or subdivisions with no or insufficient agricultural locations identified in the above procedure, grazing locations were incorporated into the agricultural distribution and FAO crop areas of the appropriate countries were redistributed among cells in the expanded distribution. For the remaining countries, in which no or insufficient agricultural locations were targeted by the preceding steps, FAO crop areas were evenly distributed throughout all land cells of the country or subdivision. With the addition of ~30 cells to allow for representation of one celled countries, most of which are islands, this initial method resulted in 4468 1° cells identified as agricultural locations for fertilizer inputs from a total of ~14,500 ice-free land cells globally. About 3425 of them were identified through non-grazing land uses; another ~860 of them were grazing cells allowed in countries with no or insufficient land-use locations; the remainder were from island countries and countries in which all cells were included because none were targeted in the preceding steps.

Although we did not use the land-use data base to calculate cropland areas directly, we evaluated the initial agricultural distribution in a general way by calculating the ratio of FAO crop area to the agricultural area for each country or

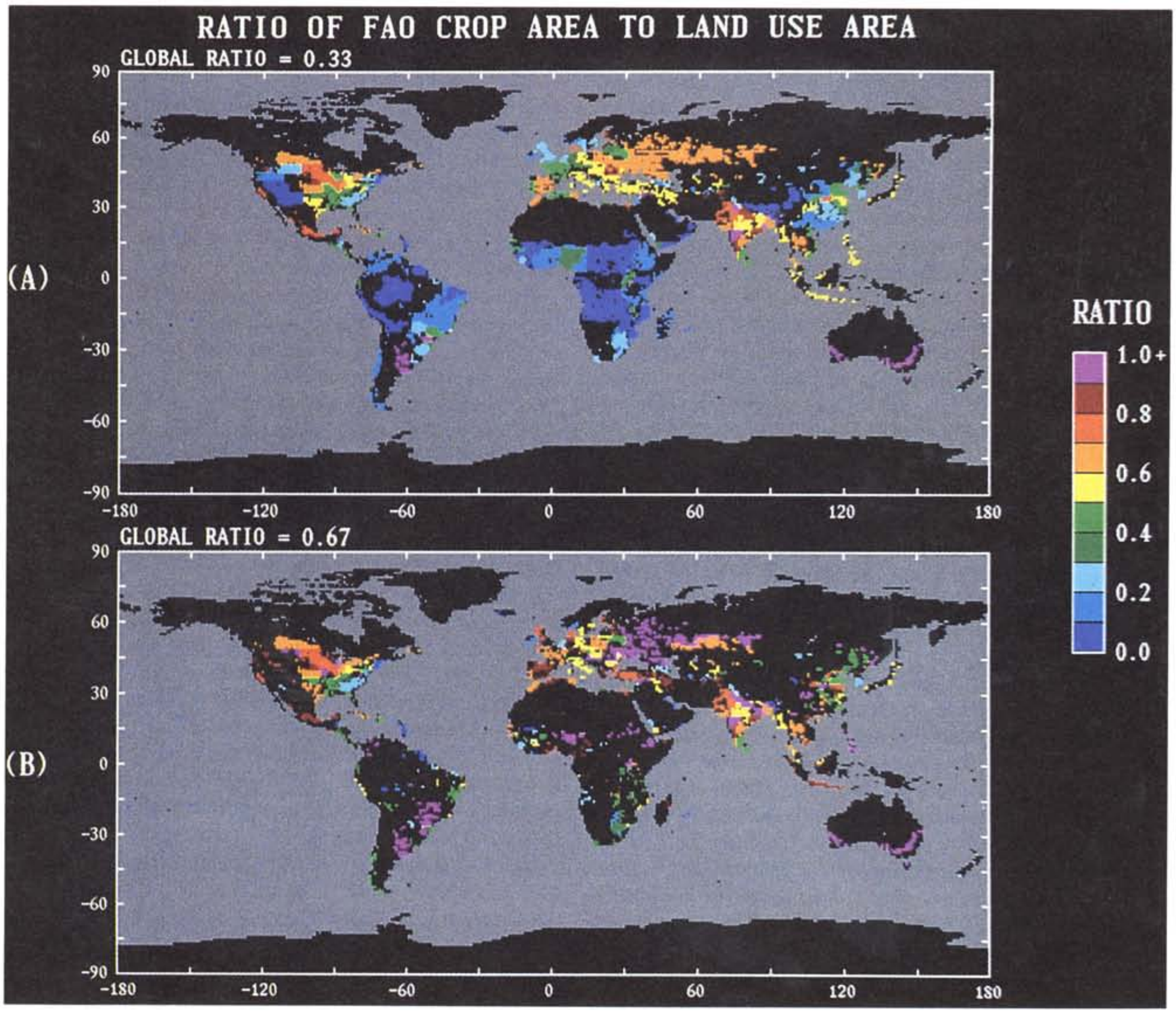

Plate 1. Ratio of Food and Agriculture Organization (FAO) crop area to agricultural area. The latter equals 100% of the area of agricultural cells. (a) Initial ratios from the unmodified land-use data set. (b) Final ratios from the modified land-use data set.

subdivision; agricultural area is 100% of the area of a country's agricultural cells. The initial distribution of ratios is shown in Plate 1a. The smaller the ratio, the greater the overestimate of agricultural extent relative to FAO cropland.

The composite global value was 0.33; ratios for individual political units ranged from <0.01 to 1.6. Ratios were generally higher for heavily agricultural developing countries (Burma, Pakistan) because agricultural systems dominate the landscape in these countries, and for developed countries with intensive, documented agricultural systems (e.g., Romania, Argentina). Ratios >1 generally mean that the agricultural area must be cropped more than once a year to account for the annual FAO crop area. These occurred in regions where multiple cropping is a common practice, e.g., the Indian states of Punjab and West Bengal.

For small countries comprising a few cells, ratios are very sensitive to inclusion or exclusion of only one cell's area and therefore are not discussed further. However, ratios for many medium and large countries/subdivisions were low. Typical values for countries in western Europe and states in the United States were 0.2-0.5 indicating that the initial distribution of fertilizer locations was overestimating the extent of agriculture by factors of 2-5. For many other countries, especially in Africa and South America, ratios were 0.05-0.10 indicating that areas of targeted agricultural locations were 10-20 times reported cropland areas. Low country ratios resulted when either too many agricultural locations were identified by the land-use data base, or when no agricultural locations were identified which defaulted to allowing all land cells of a country into the agricultural category.

Overestimating agricultural locations does not affect the calculation of N application rates because those are derived by dividing total fertilizer N consumption by FAO crop area in each country or subdivision. However, distributing FAO areas throughout too many locations results in broad regional patterns of unrealistically diffuse fertilizer consumption.

Because agricultural locations were systematically overestimated, the initial procedure was modified. The goal was to reduce areal overestimates that resulted from direct targeting of numerous land-use and grazing locations, and from default targeting of all cells in a country. Hypotheses guiding the modifications included the following: fertilizer inputs are more likely to be associated with intensive commercial farming systems characterized by dense infrastructure (e.g., roads) than with extensive subsistence agriculture; industrial/export crops are more likely to receive fertilizer inputs in a predominantly subsistence economy than are food crops [*Martinez and Diamond*, 1982]; in subsistence areas where land-use data are poor, generalized, or out of date, the density of settlements and transportation networks may be a more reliable indicator of agricultural intensity than is land-use information alone.

To implement the modifications, we exploited the detailed crop information in the land-use data set of *Matthews* [1983], and incorporated another data set, at the same resolution, representing intensity of landscape use [*Matthews*, 1983]. This subjective index, from 0 to 5, was derived from a global series of 1:1 million scale Operational Navigation Charts (Defense Mapping Agency, U.S. Department of Defense) with map dates from 1973 to 1983. Zero values indicate that no anthropogenic features of any kind are present in the 1° map cells; higher values indicate increasing density of features ranging from minimal footpaths and isolated airstrips to dense complexes of roads, railroads and cities.

Most modifications to the initial agricultural distribution were made on a country-specific basis by evaluating a country's suite of land uses, crops, and intensity indices.

To reduce targeting of numerous agricultural locations, designated land-use types for individual countries were removed from the initial agricultural distribution. These included land uses or crop combinations unlikely to be associated with fertilizer inputs. For example, 51 cells of general land-use types ("extensive mixed subsistence farming with grain" or "extensive mixed subsistence farming with tropical crops dominant") in Nigeria were removed from the distribution leaving, as fertilizer locations, 21 cells identified with cash crops such as cotton. As a result, the ratio for Nigeria increased from ~0.35 to close to 1.00. Globally, modifications such as this removed ~1150 cells in 94 countries and subdivisions.

Increasing the number of eligible agricultural locations to accommodate FAO areas, thereby reducing default inclusion of large categories, involved the following: (1) adding to the basic agricultural distribution cells with specified use intensities for individual countries (added ~12 cells), (2) replacing the initial agricultural locations of 31 countries with fewer locations of specified use intensities (net loss of ~350 cells), and (3) identifying individual cells of known agricultural activity by latitude and longitude (added ~40 cells). By providing sufficient agricultural cells to accommodate FAO areas, these changes reduced the number of appended grazing cells from ~860 in the initial procedure to ~340.

This series of revisions produced a new distribution of agricultural locations totaling 2287 cells (Plate 1b). The closer agreement between FAO crop areas and areas from the new agricultural distribution is reflected in the area ratios of individual countries which increased from 0.2-0.5 (Plate 1a) to 0.6-0.9 (Plate 1b) for many medium and large countries. The composite global ratio of the final data set used in this study is 0.67.

3. Distribution of Fertilizer Consumption and Trace-Gas Emissions

Appendix B contains complete data on fertilizer N consumption including reported and estimated partitioning of the total N among fertilizer types, by country and region, for 1984. In the following sections, we discuss spatial distributions, regional and fertilizer-type profiles, and interannual trends of regions in the 1980s.

3.1. Global Distribution of Fertilizer Consumption

Application rate is calculated for each country by distributing total fertilizer N evenly throughout FAO crop area in the country's agricultural cells. In this way, application rates vary among countries but are constant within country boundaries. The global distribution of fertilizer consumption is shown in Plate 2. Plate 2a gives application rate in kg N/ha

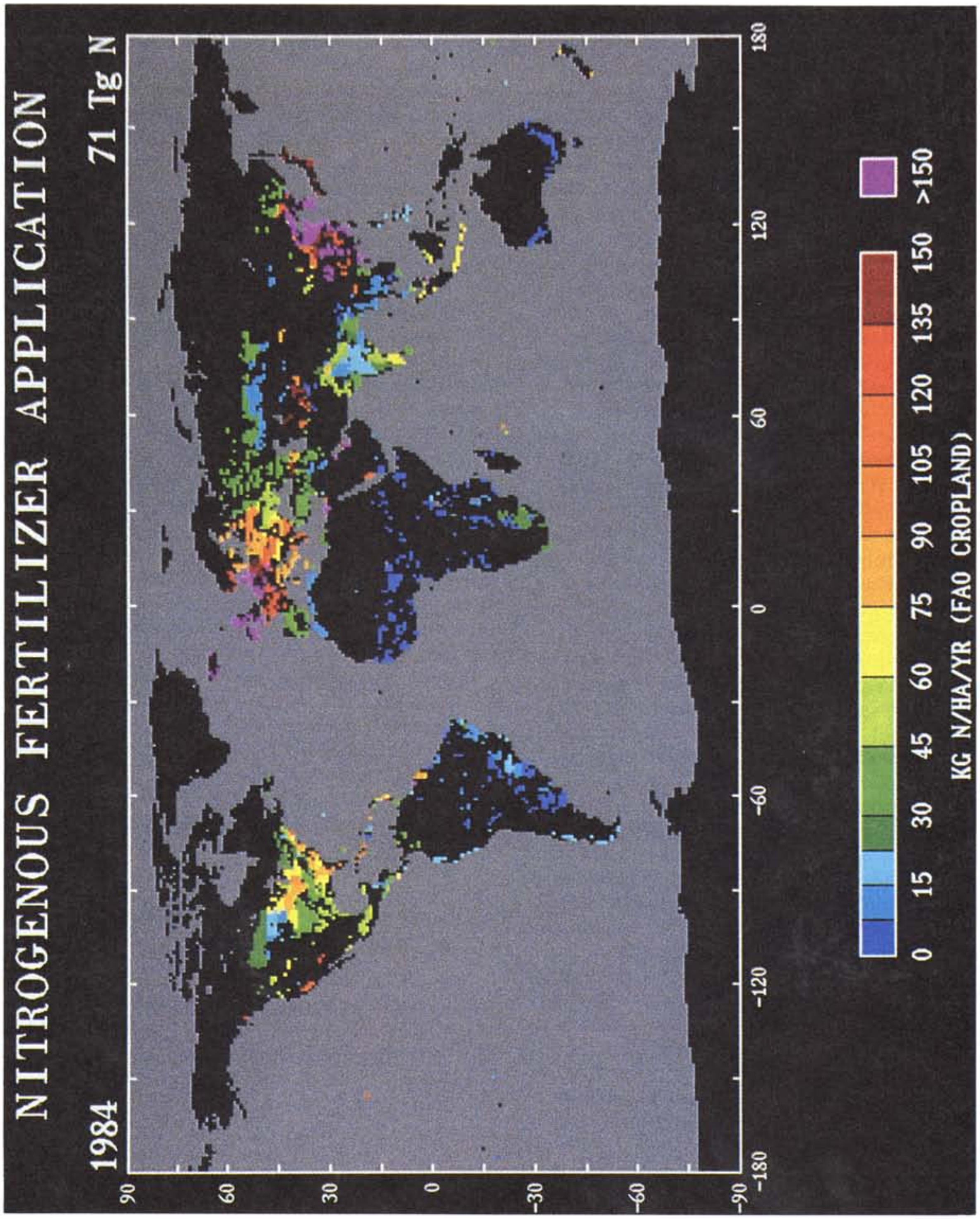

Plate 2a. Global distribution of 1984 nitrogenous fertilizer use showing N application rate, per hectare, for FAO crop area in the 1° cells.

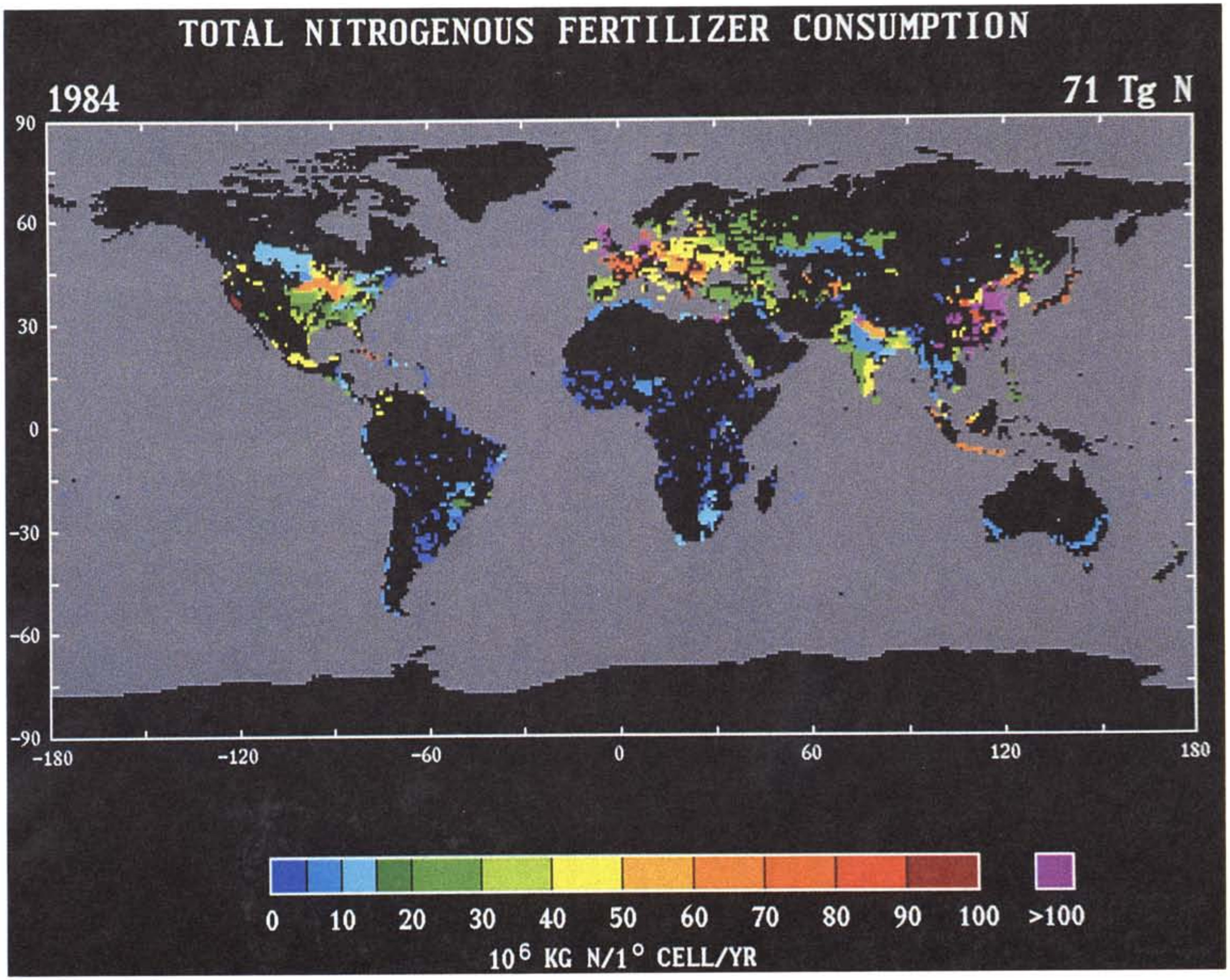

Plate 2b. Global distribution of 1984 nitrogenous fertilizer use showing total N consumption in 1° cells.

FAO cropland/year while Plate 2b shows total N consumed annually in 1° cells.

We expected the values in Plate 2a to represent the lower limit for application rates since they rely on the assumption that all crops receive fertilizer inputs. Despite this simplification, mean application rates for many countries are within 20-30% of those reported. Most countries of western Europe and East Asia show mean application rates of 75 to >150 kg N/ha/yr (Plate 2a), consistent with reported values [*Martinez and Diamond*, 1982; *Martinez*, 1990]. For example, the mean rate calculated for Japan is 145 kg N/ha/yr (Plate 2a); *Martinez* [1990] reports application rates of 176 and 103 kg N/ha/yr for wheat and rice, respectively, the two major crops receiving nitrogenous fertilizers in Japan, and an area-weighted mean of 182 kg N/ha for fertilized lands in Japan. Similarly, the area-weighted mean for South Africa reported by *Martinez* [1990] is 32 kg N/ha for fertilized land while the country mean calculated here is 29 kg N/ha for all FAO cropland; reported and calculated means for fertilizer N inputs in western Germany are 173 and 195 kg N/ha/yr, respectively.

Application rates are underestimated for countries in which (1) small areas of industrial and/or export crops receive very high fertilizer inputs while extensive areas of food and other crops receive minimal inputs or (2) unfertilized pasture is intermixed with, and perhaps reported as, cropland. The latter may occur in areas such as India, western United States, southern Russia, South Africa, and Australia. An example of the former is Tanzania which fertilized 100% of its tea and tobacco area and only 12% of the maize area in the 1970s [*Martinez and Diamond*, 1982].

These mean values emerge from the technique because most major fertilizer consumers are engaged in intensive agriculture supported by ubiquitous and large fertilizer inputs. For instance, during the late 1970s, most countries in western Europe fertilized close to 100% of crop areas and Pakistan fertilized >70% of most food, industrial and fiber crops [*Martinez and Diamond*, 1982]. Therefore, although the data set reflects anomalously low rates of N application in some countries where fertilizer use is limited to a few crops, the systematic bias toward low values is not severe, suggesting that the assumption of ubiquitous fertilizer use is a reasonable first approach.

Plate 2b shows total N consumed in 1° cells. (See Table B1, Appendix B, for country specifics). Major use regions are broadly distributed throughout north temperate areas whereas tropical/subtropical consumption is geographically confined to a few large countries. Fertilizer consumption in temperate regions (poleward of 35°) accounts for 61% of the total while the subtropics (20-35°) account for 29% and the tropics (±20°) for 9%.

The geographic character of the data developed here allows for evaluation of spatial distributions of the fertilizer source and of associated emissions, as well as for prediction of future distributions. In addition, geographic accuracy facilitates the treatment of fertilizer consumption across the range of climatic, ecological, and management environments in which it takes place and which differentially affect trace-gas emissions.

3.2. Fertilizer Consumption by Type and Region

Figure 1 illustrates regional profiles of nitrogenous fertilizer consumption by type for the 10 regions used in this study. (See Table B1, Appendix B, for country specifics.) Although these values reflect conditions for 1984, the profiles may be considered characteristic of the 1980s since major changes in regional fertilizer combinations take place gradually for large users. Table 2 shows consumption profiles as proportional contributions of fertilizer types to regional and global N use; Table 3 shows proportional contributions of regions to global and fertilizer-type totals. Fertilizer N input was close to 71 Tg N in 1984. East Asia accounted for ~37% of the total, while North America and western Europe accounted for 17% and 14% of global use, respectively. Former centrally planned economies in Europe consumed one fifth of the 1984 total but consumption patterns are variable. The most widely used chemical nitrogenous fertilizer was urea which accounted for 40% of the world's total in the mid-1980s. While almost every country consumed urea, ~75% of the large East Asian

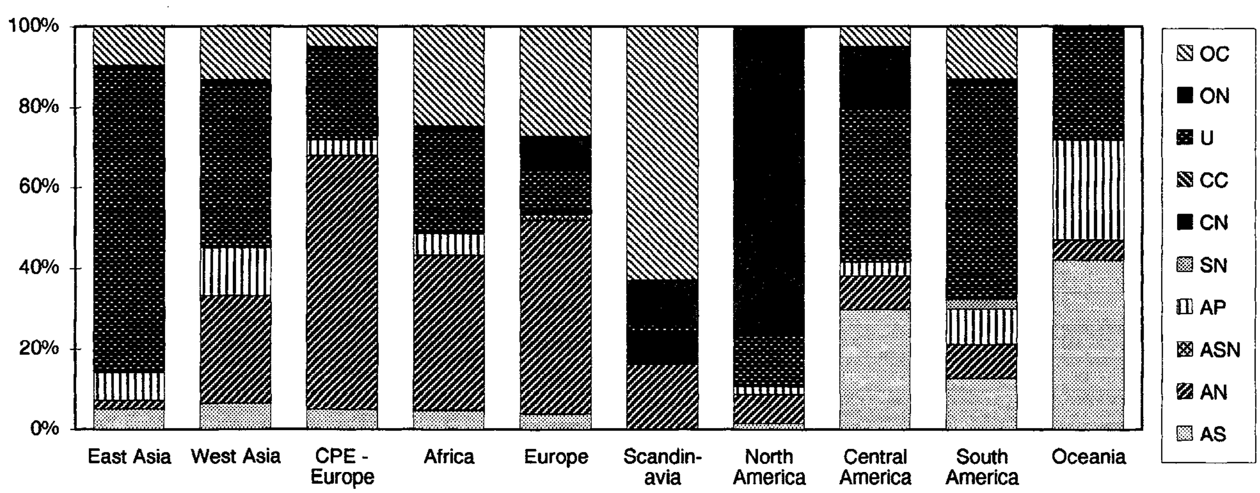

Figure 1. Regional profiles of nitrogenous fertilizer consumption by fertilizer type. CPE is centrally planned economy.

Table 2. Regional Profiles of 1984 Nitrogenous Fertilizer Consumption Showing Proportional Contribution of Fertilizer Types to Regional and Global Totals

	Region	Total N, Tg	AS	AN	ASN	AP	SN	CN	CC	U	ON	OC
1	East Asia	26.0	5	2	-	7	0	0	0	75	1	10
2	West Asia	1.9	6	27	-	12	0	-	-	41	1	13
3	Former CPEs of Europe	14.9	5	63	-	4	0	-	-	22	1	5
4	Africa	1.8	5	38	0	5	0	-	-	26	1	25
5	Europe	9.6	5	47	2	0	0	0	0	12	8	26
6	Scandinavia	1.0	0	16	-	-	0	8	-	2	11	63
7	North America	11.7	2	7	-	2	0	-	-	13	76	-
8	Central America	1.8	30	8	-	4	-	-	-	38	15	5
9	South America	1.4	13	8	-	9	3	0	0	53	1	13
10	Oceania	0.4	42	5	-	25	-	0	-	25	1	-
	Total N, Tg	70.5	3.7	17.1	0.1	3.3	0.0	0.1	0.1	28.2	10.6	7.5
	Percent of total N	100	5.2	24.3	0.1	4.7	0.0	0.1	0.1	40.0	15.0	10.6

All values, excluding total N, are in percentages. All rows, excluding total N, sum to 100. Abbreviations are AS, ammonium sulphate; AN, ammonium nitrate; ASN, ammonium sulphate-nitrate; AP, ammonium phosphate; SN, sodium nitrate; CN, calcium nitrate; CC, calcium cyanamide; U, urea; ON, other nitrogenous fertilizers; OC, other complex fertilizers.

Table 3. Regional Profiles of 1984 Nitrogenous Fertilizer Consumption Showing Proportional Contribution of Regions to Global and Fertilizer Type Totals

	Region	Total N, Tg	Total N, Percent	AS	AN	ASN	AP	SN	CN	CC	U	ON	OC
1	East Asia	26.0	36.9	36	3	-	56	0	1	48	69	2	34
2	West Asia	1.9	2.7	3	3	-	7	-	-	-	3	0	3
3	Former CPEs of Europe	14.9	21.1	20	55	-	18	0	-	52	12	1	10
4	Africa	1.8	2.5	2	4	1	3	1	-	-	2	2	6
5	Europe	9.6	13.6	10	27	99	0	12	18	-	4	7	35
6	Scandinavia	1.0	1.4	0	1	-	-	1	80	-	0	1	8
7	North America	11.7	16.6	5	5	-	7	12	-	-	6	84	-
8	Central America	1.8	2.5	14	1	-	2	-	-	-	2	3	1
9	South America	1.4	2.0	5	1	-	4	74	1	0	3	0	3
10	Oceania	0.4	0.5	4	0	-	3	0	0	-	0	0	-
	Total N, Tg	70.5		3.7	17.1	0.1	3.3	0.0	0.1	0.1	28.2	10.6	7.5

All values, excluding total N, are in percentages. All columns, excluding total N, sum to 100. Abbreviations are AS, ammonium sulphate; AN, ammonium nitrate; ASN, ammonium sulphate-nitrate; AP, ammonium phosphate; SN, sodium nitrate; CN, calcium nitrate; CC, calcium cyanamide; U, urea; ON, other nitrogenous fertilizers; OC, other complex fertilizers.

fertilizer use was supplied by this one fertilizer. Ammonium nitrate, used primarily in Europe, West Asia, Africa and the former centrally planned economies of Europe, accounted for about one quarter of global consumption.

3.3. Recent Trends in Fertilizer Consumption

Figure 2 shows consumption of fertilizer N by region for the 5 years before and after the 1984 base year of this study. Figure 3a displays growth trends in fertilizer N consumption during the 1980s; values represent consumption for each year referenced to consumption in 1979. Interannual variability in regional N consumption for 1979-1989 is illustrated in Figure 3b; each year's consumption is referenced to consumption in the immediately preceding year.

The rate of fertilizer N inputs increased at a mean annual rate of ~3.5% or ~2.5 Tg N during the decade of the 1980s although growth rates were variable (Figure 3a and 3b). Consumption rose from ~57 Tg N in 1979 to almost 80 Tg N a decade later (Figure 2). In East Asia, which accounts for almost 40% of total N, annual increases in fertilizer use have approached 10% (Figure 3b). Central America, South America, Oceania and Africa display variable but generally increasing consumption although together they account for less than 8% of total N use in the mid-1980s (Table 3). Nitrogenous fertilizer use is stabilizing in North America and Europe which accounted for 30% of 1984 use (Table 3), although interannual variations in North American consumption have been as high as 20% in the 1980s (Figure 3b). Former CPEs of Europe consumed one fifth of the 1984 total, but consumption trends are variable and a

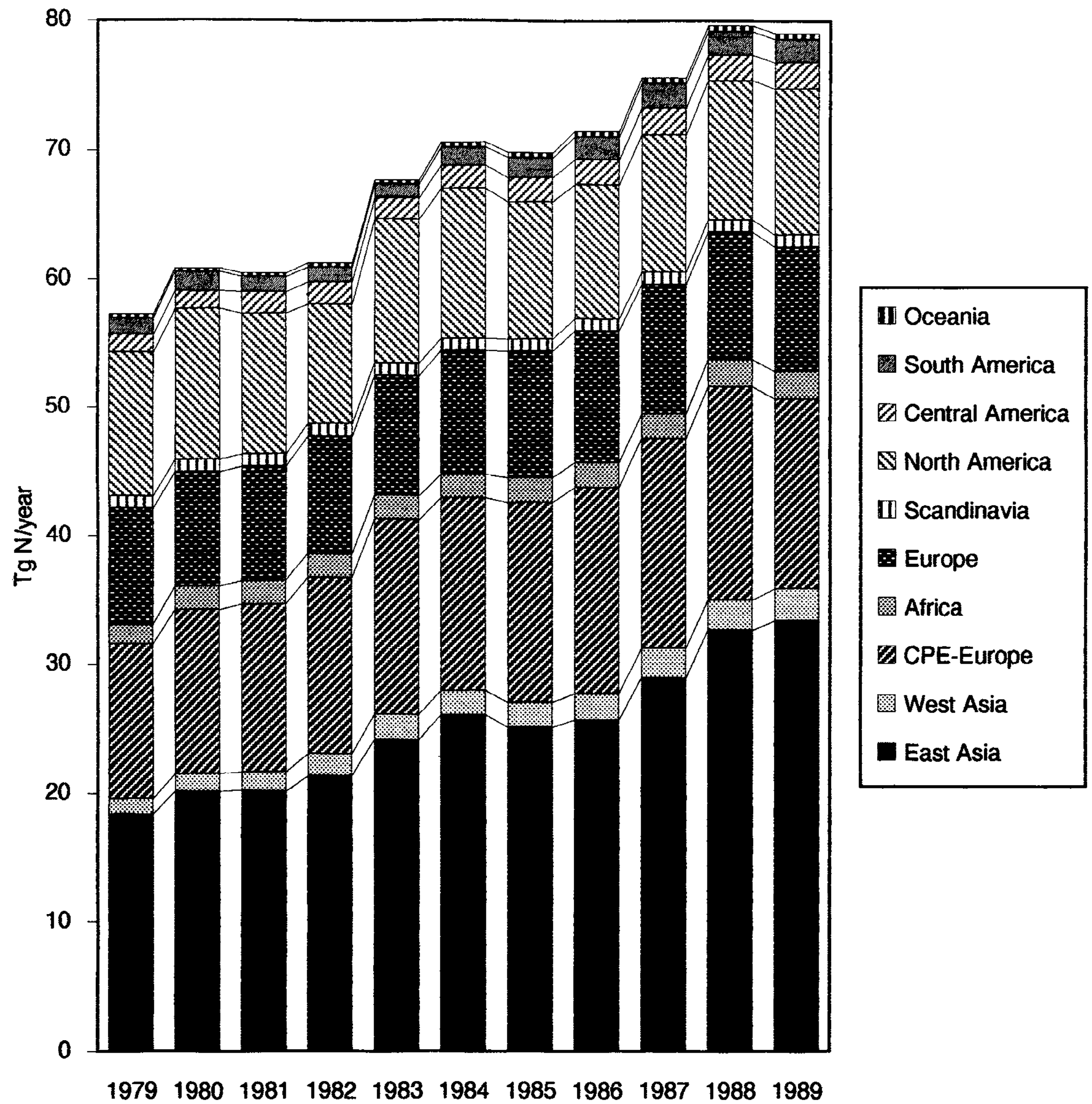

Figure 2. Annual consumption of fertilizer N by region for the 5 years preceding and following the 1984 base year of this study. Abbreviations are AS, ammonium sulphate; AN, ammonium nitrate; ASN, ammonium sulphate-nitrate; AP, ammonium phosphate; SN, sodium nitrate; CN, calcium nitrate; CC, calcium cyanamide; U, urea; ON, other nitrogenous fertilizers; OC, other complex fertilizers.

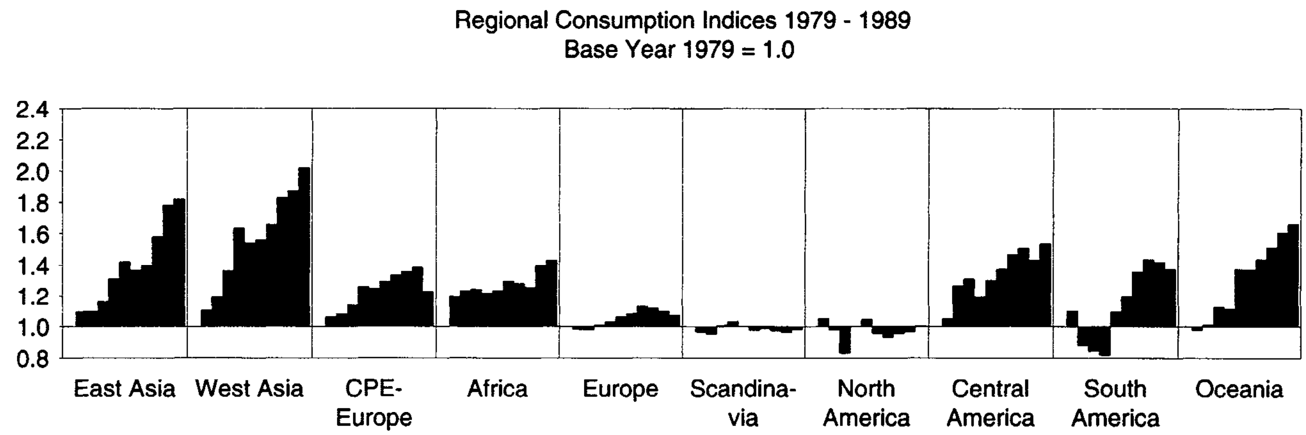

Figure 3a. Growth index of fertilizer N consumption by region for 1979-1989. Values represent consumption for each year referenced to consumption for 1979 (1979 = 1.00). Each regional section consists of 11 values covering the years from 1979 to 1989.

downward trend is apparent at the end of the decade (Figure 3b). Economic reorganizations indicate that this decline may continue.

These patterns illustrate the difficulty of predicting future consumption patterns for dynamic economies like European former CPEs, although Asian growth has averaged ~10% per annum for most of the period. This increasing Asian consumption is supported in part by increasing production capacity, particularly for urea, within the region. *Harre and Bridges* [1988] report that developing countries, which accounted for ~15% of the world's urea production capacity in 1967, accounted for ~40% by the end of the 1980s. This shift in production enhances the prospect of substantial and increasing fertilizer supply within developing regions in the future.

3.4. Nitrous Oxide Emission From Fertilizer Consumption

Nitrous oxide emissions from fertilized agricultural soils are regulated in complex ways by factors such as soil moisture status and soil oxygen status, soil type, texture, porosity and pH, organic carbon content, and microorganisms, as well as management practices including fertilizer type, application rate, and timing and technique of applications, tillage practices, crop system, irrigation, and use of other chemicals [e.g., *Bremner and Blackmer*, 1978; *Hutchinson and Mosier*, 1979; *Breitenbeck et al.*, 1980; *Bremner et al.*, 1980; *Mosier and Hutchinson, 1981*; *Mosier et al.*, 1981, 1986; *Ryden*, 1981; *Seiler and Conrad*, 1981; *Blackmer et al.*, 1982; *Duxbury et al.*, 1982; *Armstrong*, 1983; *Conrad et al.*, 1983; *Slemr et al.*, 1984; *Klemedtsson et al.*, 1988]. At present, relationships between emissions and most of these factors are not sufficiently established to incorporate into global emissions estimates. Furthermore, large-scale information about some factors (e.g., method of fertilizer application or soil pH) are lacking.

We estimated ranges for global N_2O emission from chemical fertilizer consumption using the distribution of total N usage among fertilizer types, together with median, low- and high-emission coefficients for the types taken from *Eichner's*

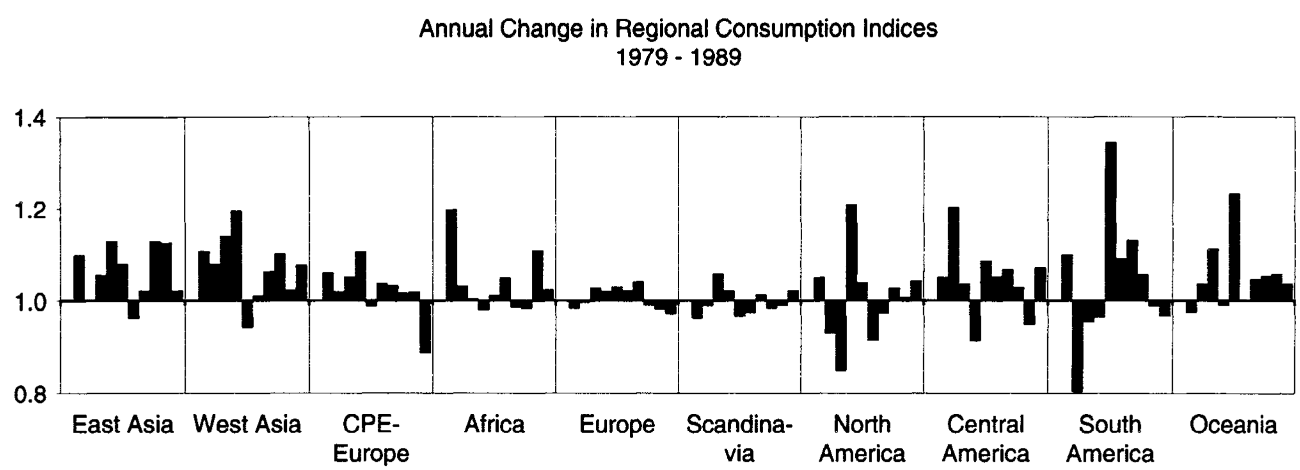

Figure 3b. Interannual variability in growth of fertilizer N consumption by region for 1979-1989. Values represent consumption for each year referenced to consumption for the immediately preceding year; the first year, 1979, is referenced to itself and equals 1.00. Each regional section consists of 11 values covering the years from 1979 to 1989.

[1990] review of field studies. *Eichner* [1990] confined the review to studies with fertilized plots paired with unfertilized controls in order to isolate the fertilizer contribution to total N_2O effluxes at the sites. Therefore, the coefficients represent the fraction of applied N evolved as N_2O (N_2O-N) and the estimate represents fertilizer-related enhancements to background fluxes of nitrous oxide. All measurements reviewed by *Eichner* [1990] were carried out in temperate regions. Currently, there are no published N_2O flux measurements from fertilized agricultural fields in tropical or subtropical sites [*Vitousek and Matson*, 1993].

Table 4 shows consumption and emission coefficients for the fertilizers identified in this study. (Note that in order to show smaller values, the unit for fertilizer consumption and N_2O-N emission here is 10^9 g N instead of 10^{12} g (Tg) as used previously.) Due in part to the absence of tropical/subtropical measurements, coefficients for each fertilizer were kept constant for all regions although the response of agricultural systems in low latitude environments to fertilizer amendments has not been quantified.

As noted above, consumption of urea (U) and ammonium nitrate (AN) account for almost 65% of total fertilizer N use and 73% of the N_2O emission estimate. In addition, they are significant components in the fertilizer complement of East Asia and CPEs of Europe, which are large consumers with high decadal growth rates, as well as of Europe which is characterized by relatively stable consumption.

Nitrous oxide emission from chemical fertilizer use is estimated at ~100 x 10^9 g N_2O-N (0.1 Tg N_2O-N) in 1984 with a range of ~29-2,000 x 10^9 g N_2O-N (0.03 to 2.0 Tg N_2O-N). This equals <1% to 3% of the total nitrogen applied via commercial fertilizers and represents <1% to 15% of the annual emission of N_2O from terrestrial sources [*Davidson, 1991*; *Khalil and Rasmussen, 1992*]. *Eichner* [1990] suggests that emissions may be twice this value since these coefficients account only for those emissions occurring during the growing/measurement season and do not include N_2O emissions from drainage and leaching in agricultural areas. This estimate is very close to previous estimates over the past dozen years [*Weiss*, 1981; *Conrad et al.*, 1983; *Slemr et al.*, 1984; *Eichner*, 1990]. However, the geographic nature of these data will allow a more complete evaluation of climatic, environmental and management influences on emissions.

Plate 3 shows the spatial distribution of annual nitrous oxide emissions from fertilizers based on the median estimate presented in Table 4 . Note that values are N_2O-N emissions per hectare of FAO cropland only. Of the total emission of 0.1 Tg N_2O-N, temperate regions (>35°) account for 69% while the subtropics (20-35°) account for 24% and the tropics (±20°) for 7%. By comparison, *Bouwman et al.* [1993] suggest a total source of 6.8 Tg N_2O-N from undisturbed soils with 80% emanating from tropical/subtropical regions within 30° of the equator.

Presently, it is unclear whether measurements in tropical and subtropical agricultural ecosystems will revise this low latitude estimate or confirm emissions similar to those in temperate environments. Nevertheless, absolute and relative contributions of the low latitudes are expected to increase in the future since growth rates of the recent decade are expected to continue (Figure 3a).

3.5. Ammonia Emission From Fertilizer Consumption

A recent assessment of the global ammonia budget for the late 1980s suggests a total annual ammonia source of 75 Tg N including emissions of ~8 Tg N from fertilizer production and 10 Tg N from undisturbed soils [*Schlesinger and Hartley*, 1992]. Field measurements of ammonia emission following fertilization of agricultural sites in temperate regions range from 1-46% of applied fertilizer N [*Schlesinger and Hartley*, 1992]. Measurements in flooded rice fields of Australia, China, Malaysia, and the Philippines indicate that ammonia volatilization accounts for losses of 2-56% of applied N and

Table 4. Ranges for Global Estimates of Nitrous Oxide Emission From Nitrogenous Fertilizer Consumption

Fertilizer Type	Fertilizer Consumption, 10^9 g N	Emission Coefficient, % Median	Emission Coefficient, % Range	Emission, 10^9 g N_2O-N Median	Emission, 10^9 g N_2O-N Range
Ammonium sulphate	3,654	0.12	0.02 - 1.5	4	1 - 55
Ammonium nitrate	17,054	0.26	0.04 - 1.71	45	7 - 292
Ammonium sulphate-nitrate	147	0.26	0.02 - 1.5	0	0 - 2
Ammonium phosphate	3,272	0.12	0.02 - 1.5	4	1 - 49
Sodium nitrate	52	0.05	0.01 - 0.5	0	0 - 0
Calcium nitrate	99	0.03	0.001 - 0.5	0	0 - 1
Calcium cyanamide	62	0.03	0.001 - 0.5	0	0 - 0
Urea	28,215	0.11	0.07 - 1.5	31	19 - 423
Other nitrogenous fertilizers	10,431	0.11	0.01 - 6.84	12	1 - 725
Other complex fertilizers	7,519	0.11	0.01 - 6.84	8	0 - 514
Total	70,505			105	29 - 2,061

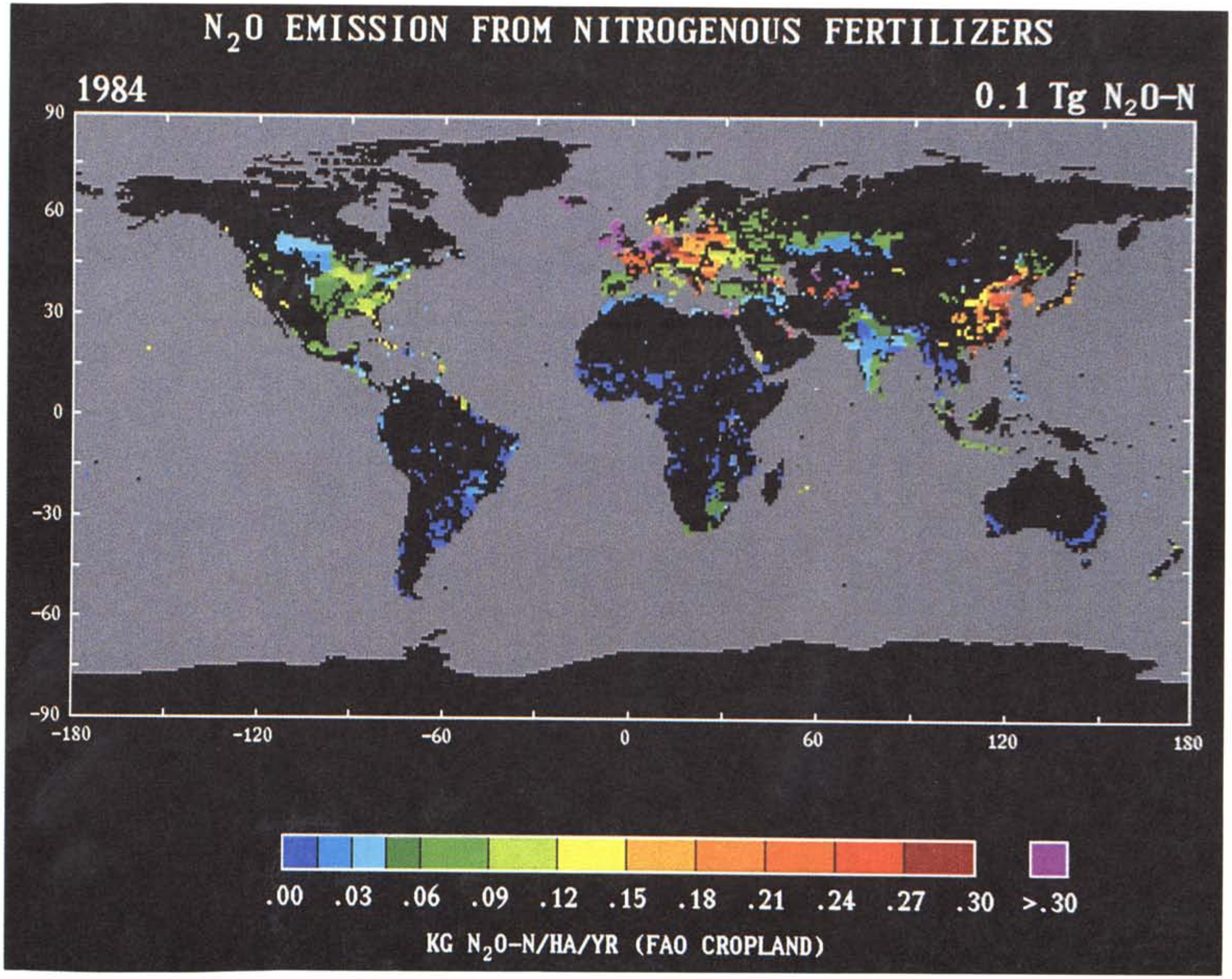

Plate 3. Global distribution of nitrous oxide emission from nitrogenous fertilizers. N_2O-N emission rate, per hectare, for FAO crop area in the 1° cells.

that the higher rates are consistently associated with urea treatments [*Freney et al.*, 1989].

Applying emission coefficients to the suite of fertilizer types produced in 1988-1989, *Schlesinger and Hartley* [1992] conclude that as much as ~10% of fertilizer N may be lost as volatile ammonia. Table 5 shows their suggested emission coefficients applied to the 1984 data developed in this study. *Buijsman et al.* [1987] also relied on field studies to derive emission factors for a study of European ammonia sources. On the basis of fertilizer types consumed in Europe, *Buijsman et al.* [1987] estimate losses of ~6% of fertilizer N in the form of ammonia. Applying *Buijsman et al.*'s emission coefficients to global fertilizer consumption in 1984 results in a slightly larger fraction (8%) of fertilizer N volatilized to ammonia due to proportionately larger urea consumption in Asia (Table 5).

The global totals based on *Schlesinger and Hartley* [1992] and *Buijsman et al.* [1987] are similar, ~7 and ~5.5 Tg NH_3-N per year, respectively. Although urea and ammonium nitrate are the two largest contributors in both studies, emission coefficients for individual fertilizers vary by factors of 2 to 4 between the studies, producing large differences in proportional contributions of fertilizer types to the total emission. This is particularly evident for urea and ammonium nitrate which account for 40% and 24%, respectively, of global fertilizer N consumption. Using identical consumption statistics, urea accounts for 80% of the ammonia estimate based on *Schlesinger and Hartley*'s [1992] evaluation and 52% of *Buijsman et al.'s* [1987] while ammonium nitrate contributes 6% and 31% of the ammonia emission estimated from *Schlesinger and Hartley* [1992] and *Buijsman et al.* [1987], respectively. Emission coefficients adopted by *Dentener and Crutzen* [1994], composited from these same sources, give a global emission of ~5.5 Tg NH_3-N when applied to the 1984 data.

Similarities among these studies do not reflect low uncertainty in estimates of ammonia volatilization but, rather, a reliance on the same small suite of field studies and dependence on identical sources for fertilizer data. In light of the variation in regional profiles of fertilizer partitioning (Figure 1), uncertainty in emission coefficients for individual fertilizers translates into uncertainties in the global distribution of the fertilizer-derived ammonia source. Other factors identified as potential controllers of fluxes, e.g., temperature, and soil characteristics such as pH, texture and moisture status [*Freney et al.*, 1989], are not included in any of the studies and remain poorly quantified.

The geographic distribution of ammonia emission from fertilizers based on *Schlesinger and Hartley's* [1992] emission coefficients and the 1984 data is shown in Plate 4. Annual fluxes of NH_3-N from agricultural lands are about 100 times those of N_2O-N from the same areas (Plate 3). In broad terms, temperate regions (poleward of 35°) account for 45% of the total NH_3-N emission while the subtropics (20-35°) account for 41% and the tropics (±20°) for 14% in this exploratory scenario. However, as with nitrous oxide emissions, measurements in tropical and subtropical environments are not numerous and fluxes remain poorly characterized.

4. Uncertainties and Improvements

4.1 Fertilizer Consumption

FAO yearbooks are prepared from reports submitted by individual countries and are the most complete global source of fertilizer information available. With rare exceptions, fertilizer information from country agricultural statistics is identical to that of FAO. Occasionally (e.g., India, United States) statistics published by individual countries provide more detail about consumption of fertilizer types.

Available studies confirm higher ammonia volatilization rates for urea and ammonium-sulphate, -nitrate and -phosphate while differences in N_2O emissions among types are less clear. More specific information about consumption of types will be needed if differential coefficients are strongly confirmed. For N_2O emissions, information about consumption of aqua- and

Table 5. Global Estimates of Ammonia Emission From Nitrogenous Fertilizer Consumption

Fertilizer Type	Fertilizer Consumption, 10^9 g N	Emission Coefficient, % SH	Emission Coefficient, % Buijsman	Emission, 10^9 g NH_3-N SH	Emission, 10^9 g NH_3-N Buijsman
Ammonium sulphate	3,654	10	15	370	555
Ammonium nitrate	17,054	2.5	10	428	1,710
Ammonium sulphate-nitrate	147	3	12.5	3	13
Ammonium phosphate	3,272	3	5	99	165
Sodium nitrate	52	3	1	3	1
Calcium nitrate	99	3	2	3	2
Calcium cyanamide	62	3	1	3	1
Urea	28,215	20	10	5,640	2,820
Other nitrogenous fertilizers	10,431	3	1	318	106
Other complex fertilizers	7,519	3	1	225	75
Total	70,505			7,092	5,448

Emission coefficients are from *Schlesinger and Hartley* [1992] (SH) and from *Buijsman et al.* [1987] (Buijsman).

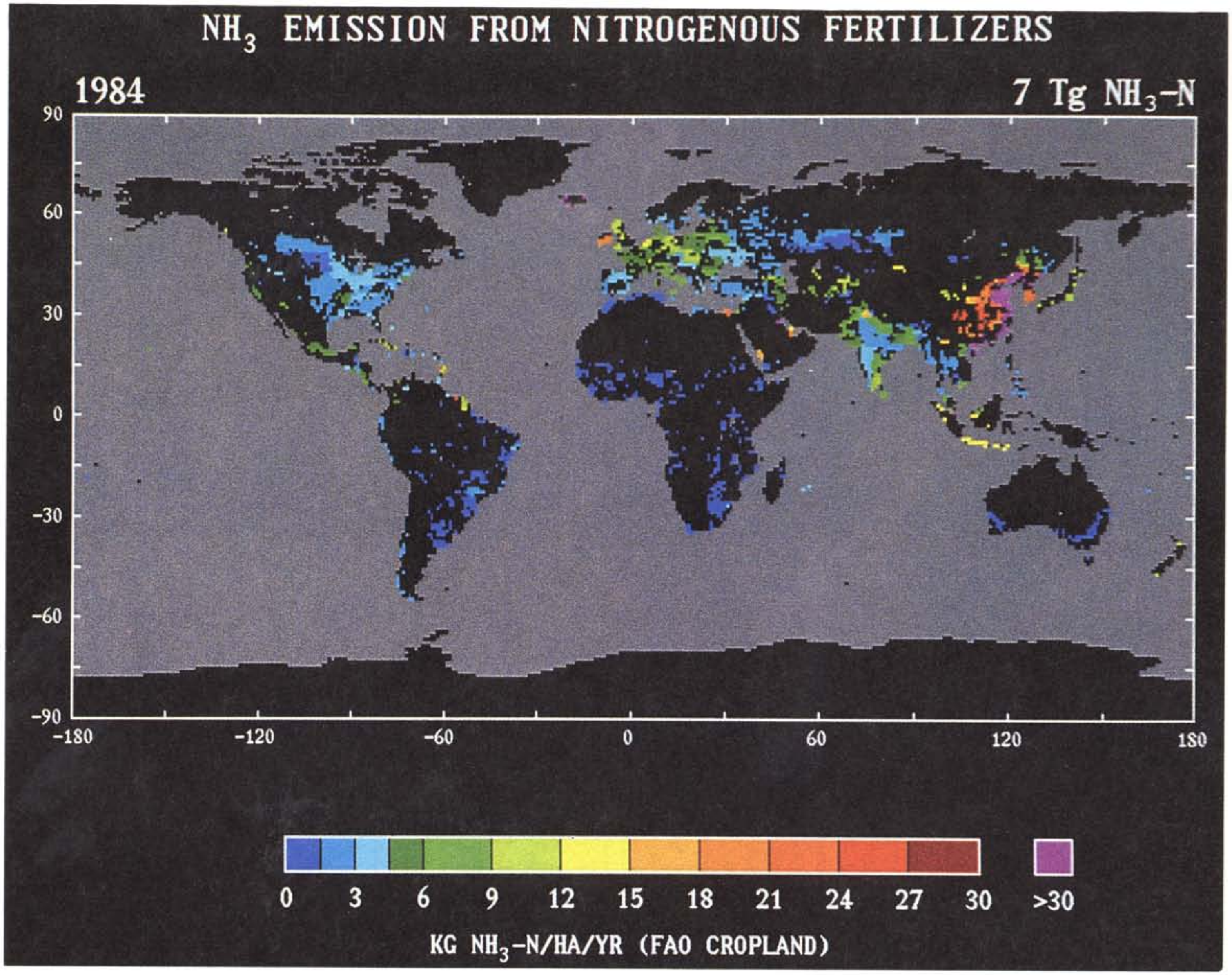

Plate 4. Global distribution of ammonia emission from nitrogenous fertilizers based on emission coefficients of *Schlesinger and Hartley* [1992]. NH_3-N emission rate, per hectare, for FAO crop area in the

anhydrous-ammonia fertilizers, available for the United States and Canada where these fertilizers are primarily used, might be incorporated in future.

We have estimated global distributions of N inputs only from the use of nitrogenous chemical fertilizers; the contribution of organic fertilizers to consumption and emissions is not included. Although fertilizer N input and associated trace-gas emissions are dominated by the commercial fertilizers included in this study, the use of organic fertilizers is significant in some regions such as Southeast Asia. However, we are unaware of information reliable and complete enough to incorporate at the present time.

4.2. Fertilizer Application Rates

In section 3.1 we presented the global distribution of annual N application rates determined from FAO statistics on fertilizer consumption and crop area. Approximately 71,000 x 10^6 kg N used equally over all ~1,500 x 10^6 ha cropland gives a global mean application rate of ~47 kg N/ha. Actual application rates range from zero to >500 kg N/ha/yr for specific crops in individual countries. However, the assumption of 100% fertilization of crop areas reproduces mean application rates for many countries that are within 20-30% of those reported although within-country variations are not captured.

In countries where fertilizer use is restricted to a few crops, application rates for specialized crops can reach hundreds of kg N per hectare annually [*Martinez*, 1990; *Martinez and Diamond*, 1982] while remaining crops receive little input. In these cases, the assumption that all crop areas in the country are fertilized, and that the application rate is constant, underestimates the mean N application rate for the country's fertilized areas. If the rate of N application, rather than total N consumed, is the major determinant of N_2O and NH_3 emissions, more precise information on local fertilizer application rates and distributions of fertilized crops will be required in order to capture geographic variations within large and agriculturally diverse countries.

4.3. Seasonality and Environments of Consumption

This study focused on annual patterns of fertilizer use with no effects of seasonal environmental effects included. Intraannual variations in temperature and moisture conditions of the atmosphere and soil, as well as crop phenology and water and soil chemistry, can affect the production and release of trace gases. In addition, the natural cycle of some of these influences (e.g., water status) is modified by management practices (e.g., irrigation). Seasonality of fertilizer inputs can be derived by developing crop-fertilizer combinations and driving the seasonality of N applications using cropping cycles for fertilizer-consuming crops. Coupling of seasonal climate with seasonal distributions of fertilizer N inputs may improve estimates of trace-gas production and emission if the impact of climate on fluxes is better quantified. Acquiring reliable, large-scale information on management practices such as application method and water depth will likely be more difficult.

4.4. Trace-Gas Emissions

The paucity of flux measurements in tropical and subtropical agricultural sites representative of conditions in which fertilizers are used contributes the greatest uncertainty to emission estimates. The large and increasing concentration of fertilizer use in these regions indicates that overall uncertainty will increase without a more comprehensive measurement strategy. The problem is somewhat less severe for ammonia emission since a multicountry study of NH_3 volatilazation from flooded rice fields was conducted in the late 1980s [*Freney et al.*, 1989].

5. Discussion and Conclusion

Chemical fertilizer consumption in the mid-1980s was ~70 Tg N per year and averaged increases of ~3.5% per year during the decade of the 1980s. The most commonly used fertilizers were urea, which accounted for 40% of total fertilizer N use in the 1980s, and ammonium nitrate, which accounted for about one quarter of total use. Despite the variability in emission coefficients of N_2O and NH_3 from fertilizers, these fertilizers may have comparatively high N_2O emissions while large fractions of urea appear to be volatilized to ammonia.

Largest proportional increases in N consumption during the last decade occurred among the largest regional consumers. These include East Asia, which used 37% of 1984 total (urea was three fourths of regional use), and former CPEs of Europe which accounted for 21% of 1984 use, dominated by ammonium nitrate (63% of the region's use). North America consumed about 17% of the world's fertilizer N but consumption in North America, western Europe and Scandinavia is stabilizing (Figure 3a and 3b).

Using the distribution of N consumption among fertilizer types with a range of emission coefficients based on field studies, N_2O emission from chemical fertilizer use was estimated at 0.1 Tg N_2O-N/year with a range of 0.03 to 2.0 Tg/year for 1984. The estimated ranges presented here equal <1 to 3% of the total nitrogen applied via commercial fertilizers and represent <1% to 15% of the annual emission of N_2O from terrestrial sources [*Davidson*, 1991; *Khalil and Rasmussen*, 1992]. According to *Eichner* [1990], accounting for emissions occurring outside the growing or measurement season and from drainage and leaching in agricultural areas may double the estimate.

Since no measurements of fertilizer-derived nitrous oxide emissions are available for agricultural fields in the tropics or subtropics, the contribution of low-latitude fertilizer use of nitrous oxide emissions is considered highly uncertain. The forest fertilization study conducted by *Keller et al.* [1988] in Brazil suggests that temperate studies may not be applicable to the climate, ecology, and management characteristics of tropical and subtropical environments. This uncertainty may also apply to estimates of fertilizer-related ammonia fluxes due to the scarcity of measurements in geographically and ecologically representative environments. However, measurements of ammonia volatilization from urea amendments in flooded rice fields in China, Malaysia, Philippines, and Australia indicate that these climatically and agriculturally diverse environments exhibit ammonia emissions comparable to the high rates measured from nonflooded temperate crops [*Freney et al.*, 1989].

Assuming that the ~4% annual increase in consumption of fertilizer N during the 1980s corresponds to a 4% increase in release of N_2O-N, annual increases in emissions from fertilizer use are <0.01-0.08 Tg N_2O-N for the median case, equal to 1-2% of the current growth rate of ~3 Tg N_2O-N in atmospheric nitrous oxide [*Prinn et al.*, 1990; *Watson et al.*, 1992].

In broad geographic terms, temperate regions (poleward of 35°) and tropical/subtropical regions (within 35° of the equator) account for 61% and 39%, respectively, of commercial fertilizer consumption. In initial estimates of N emissions, these regions contribute 69% and 31%, respectively, of nitrous oxide emissions, and 45% and 55%, respectively, of ammonia emissions. However, while we are fairly confident about the overall pattern of fertilizer distributions, the nitrous oxide and ammonia distributions remain speculative.

Quantitative relationships between N emissions and the climatic, ecological and management factors affecting emission (temperature, physical and chemical properties of soils, fertilizer type, fertilizer application rates and methods, water and oxygen status of the soil, crop cover etc.) must be strengthened. We lack sufficient information to confirm the role of fertilizers in current N emissions, although this work is consistent with the conclusion of *Prinn et al.* [1990] that the increasing trend in atmospheric N_2O concentrations is likely a combination of growing tropical and midlatitude sources. Tropical increases are likely driven by expanding land disturbance as well as increasing fertilizer consumption [*Matson and Vitousek*, 1990]. The large growth trends in fertilizer consumption exhibited by developing tropical and subtropical countries during the 1980s will probably continue, supported by increasing fertilizer production capacity in these same countries.

The data presented here are designed to be used in biosphere models [e.g., *Parton et al.*, 1987, 1988, 1989; *Raich et al.*, 1991; *McGuire et al.*, 1992; *Melillo et al.*, 1993; *Potter et al.*, 1993], and in atmospheric-chemical models [*Buijsman et al.*, 1987; *Levy and Moxim*, 1989; *Taylor*, 1992; *Chameides et al.*, 1994; *Dentener and Crutzen*, 1994; *Galloway et al.*, 1994] to test hypotheses about global budgets of N_2O, NH_3, NO, and other biogeochemical cycles. The data, along with data sets on climate, soil characteristics, land cover, and relevant human activities, can facilitate the incorporation of ecological, climatic and management influences into improved estimates and predictions of trace-gas emissions.

Appendix A. Data Sources By Region

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Appendix B. Regional Nitrogenous Fertilizer Consumption for 1984

All values in Table B1 are in 10^9 g nitrogen. Column totals may not be exact due to rounding.

The Year column indicates the year for which the distribution of total fertilizer among types was taken. Partitioning of fertilizer types for 1984-1985 was used when provided; these cases are marked with an asterisk. For countries which did not report 1984-1985 divisions but

Table B1. Nitrogenous Fertilizer Consumption By Region, Country, and Type, for 1984

	Year	Total N	AS	AN	ASN	AP	SN	CN	CC	U	ON	OC
Region 1, East Asia												
India	*	5,333	99	98	-	579	-	-	-	4,300	18	239
Indonesia	3	1,285	92	-	-	-	0	1	-	1,188	-	5
Pakistan	*	935	15	109	-	67	-	-	-	657	-	86
Japan	*	697	206	10	-	-	-	-	30	106	43	302
Korea, South	1	402	3	-	-	-	-	-	-	219	-	180
Bangladesh	*	399	2	-	-	13	-	-	-	383	-	2
Malaysia	2	249	42	14	-	-	-	-	-	130	-	63
Philippines	*	178	22	-	-	19	-	-	-	115	4	18
Burma	*	127	-	-	-	-	-	-	-	127	-	-
Sri Lanka	*	96	19	-	-	-	-	-	-	56	-	21
Afghanistan	5	40	-	-	-	6	-	-	-	34	-	-
Nepal	5	32	0	-	-	-	-	-	-	20	-	11
Subtotal		9,773	499	232	-	683	0	1	30	7,336	65	927
Percent of subtotal		100	5	2	-	7	0	0	0	75	1	10
China		15,076	754	302	-	1,055	-	-	-	11,307	151	1,508
Korea, North		597	30	12	-	42	-	-	-	448	6	60
Vietnam		310	16	6	-	22	-	-	-	233	3	31
Thailand		243	12	5	-	17	-	-	-	182	2	24
Mongolia		12	1	0	-	1	-	-	-	9	0	1
Papua/New Guinea		3	0	0	-	0	-	-	-	3	0	0
Singapore		2	0	0	-	0	-	-	-	2	0	0
Bhutan		0	0	0	-	0	-	-	-	0	0	0
Cambodia		1	0	0	-	0	-	-	-	0	0	00
Subtotal		16,244	812	325	-	1,137	-	-	-	12,183	162	1,624
Total, Region 1		26,017	1,311	557	-	1,821	27	1	30	19,519	228	2,551
Region 2, West Asia												
Turkey	*	955	93	417	-	78	-	-	-	185	-	182
Iran	3	487	8	3	-	134	-	-	-	342	-	-
Saudi Arabia	*	130	-	-	-	-	-	-	-	97	-	33
Syria	*	127	-	35	-	-	-	-	-	84	-	8
Israel	3	52	11	15	-	-	-	-	-	9	7	10
Cyprus	*	10	1	2	-	-	-	-	-	2	5	-
Jordan	7	7	1	-	-	0	-	-	-	4	-	1
United Arab Emir.	1	3	1	-	-	-	-	-	-	1	-	1
Yemen (DPR)	*	2	-	-	-	-	-	-	-	2	-	-
Kuwait	5	0	-	-	-	-	-	-	-	0	-	-
Oman	*	0	0	-	-	-	-	-	-	-	-	0
Subtotal		1,773	116	471	-	212	-	-	-	726	13	235
Percent of subtotal		100	6	27	-	12	-	-	-	41	1	13
Iraq		73	4	20	-	9	-	-	-	30	1	9
Lebanon		17	1	5	-	2	-	-	-	7	0	2
Yemen (AR)		15	1	4	-	2	-	-	-	6	0	2
Qatar		1	0	0	-	0	-	-	-	0	0	0
Bahrain		0	0	0	-	0	-	-	-	0	0	0
Subtotal		106	6	29	-	13	-	-	-	43	1	14
Total, Region 2		1,879	122	500	-	224	-	-	-	770	14	249

Table B1. (continued)

	Year	Total N	AS	AN	ASN	AP	SN	CN	CC	U	ON	OC
						Region 3, Former Centrally Planned Economies of Europe						
Poland	*	1,239	89	805	-	80	0	-	-	223	0	42
Hungary	*	626	3	337	-	-	-	-	-	201	22	64
Albania	*	75	-	75	-	-	-	-	-	-	-	-
Subtotal		1,939	91	1,217	-	80	0	-	-	424	22	106
Percent of subtotal		100	5	63	-	4	0	-	-	22	1	5
Former Soviet Union		10,277	514	6,475	-	411	-	-	-	2,261	103	514
Romania		857	43	540	-	34	-	-	-	189	9	43
Former E. Germany		697	35	439	-	28	-	-	-	153	7	35
Czechoslovakia		692	35	436	-	28	-	-	-	152	7	35
Bulgaria		479	24	302	-	19	-	-	-	105	5	24
Subtotal		13,002	650	8,191	-	520	-	-	-	2,860	130	650
Total, Region 3		14,941	741	9,408	-	600	0	-	-	3,284	152	756
						Region 4, Africa						
Morocco	5	104	11	23	-	14	-	-	-	40	-	16
Algeria	5	83	-	64	-	-	-	-	-	-	-	19
Zimbabwe	5	72	0	45	-	-	0	-	-	9	-	17
Tunisia	5	42	-	40	-	-	-	-	-	-	-	1
Sudan	*	41	-	-	-	-	-	-	-	41	-	-
Zambia	5	37	0	2	-	-	-	-	-	23	-	12
Kenya	*	36	2	6	1	12	-	-	-	6	5	4
Malawi	3	28	3	17	-	-	0	-	-	4	-	4
Cameroon	8	26	3	-	-	-	-	-	-	11	-	12
Tanzania	5	24	5	7	-	-	-	-	-	10	-	2
Ethiopia	5	13	-	-	-	8	-	-	-	5	-	-
Mauritius	3	11	2	1	-	0	-	-	-	0	-	7
Benin	5	5	0	-	-	1	-	-	-	2	-	1
Swaziland	5	5	2	0	-	0	-	-	-	2	0	0
Zaire	3	5	0	-	-	-	-	-	-	3	-	2
Burkina Faso	5	4	0	-	-	-	-	-	-	1	-	2
Mozambique	5	3	1	1	-	-	-	-	-	1	-	1
Angola	5	3	0	1	-	-	-	-	-	-	-	1
Togo	3	2	0	-	-	-	-	-	-	1	1	-
Malagasy	6	2	-	-	-	0	-	-	-	2	-	0
Niger	2	1	-	-	-	-	-	-	-	1	-	0
Gambia	*	1	-	-	-	-	-	-	-	-	-	1
Congo	*	1	-	-	-	-	-	-	-	-	-	1
Burundi	*	1	-	-	-	-	-	-	-	0	-	1
Gabon	6	1	0	-	-	0	-	-	-	0	-	0
Sierra Leone	3	1	-	-	-	-	-	-	-	0	-	0
Liberia	*	0	-	0	-	-	-	-	-	-	-	-
Uganda	6	0	-	0	-	-	-	-	-	0	-	-
Guinea	*	0	-	-	-	-	-	-	-	-	-	0
Subtotal		548	29	208	1	36	0	-	-	163	7	105
Percent of subtotal		100	5	38	0	7	0	-	-	30	1	19
South Africa	5	406	13	162	-	-	-	-	-	48	-	182
Egypt		649	32	247	-	45	-	-	-	195	6	123
Nigeria		131	7	50	-	9	-	-	-	39	1	25

Table B1. (continued)

	Year	Total N	AS	AN	ASN	AP	SN	CN	CC	U	ON	OC
Libya		56	3	21	-	4	-	-	-	17	1	11
Mali		15	1	6	-	1	-	-	-	5	0	3
Senegal		15	1	6	-	1	-	-	-	5	0	3
Ivory Coast		10	1	4	-	1	-	-	-	3	0	2
Ghana		5	0	2	-	0	-	-	-	2	0	1
Chad		3	0	1	-	0	-	-	-	1	0	1
Reunion		3	0	1	-	0	-	-	-	1	0	1
Somalia		3	0	1	-	0	-	-	-	1	0	0
Rwanda		1	0	0	-	0	-	-	-	0	0	0
Central African Rep.		1	0	0	-	0	-	-	-	0	0	0
Lesotho		1	0	0	-	0	-	-	-	0	0	0
Mauritania		0	0	0	-	0	-	-	-	0	0	0
Botswana		0	0	0	-	0	-	-	-	0	0	0
Subtotal		894	45	340	-	63	-	-	-	268	9	170
Total, Region 4		1,848	87	710	1	99	0	-	-	479	16	457
					Region 5, Europe							
United Kingdom	7	1,580	-	822	-	-	-	-	-	126	93	539
France	5	2,337	39	1,017	-	-	-	-	0	215	498	569
Former W. Germany	*	1,452	52	918	91	-	-	1	22	-	13	355
Italy	*	1,017	82	220	-	-	0	11	8	378	14	304
Spain	*	915	86	369	43	-	3	2	0	174	58	180
Netherlands	*	485	1	406	-	0	3	3	-	1	8	64
Greece	3	427	57	181	-	-	-	-	-	7	-	182
Ireland	5	330	5	121	-	-	-	-	-	63	-	140
Austria	3	161	0	93	-	3	-	0	0	1	6	58
Belgium	5	146	3	98	-	-	-	-	-	3	9	34
Portugal	3	123	18	58	3	3	-	1	0	5	1	35
Switzerland	*	71	2	41	-	2	-	0	1	15	-	11
Luxemburg	5	49	1	33	-	-	-	-	-	1	3	11
Malta	*	1	0	-	-	-	-	-	-	-	-	0
Subtotal		9,093	345	4,376	136	7	6	18	32	988	702	2,483
Percent of subtotal		100	4	48	2	0	0	0	0	11	8	27
Yugoslavia		469	19	225	9	-	-	-	-	52	38	127
Subtotal		469	19	225	9	-	-	-	-	52	38	127
Total, Region 5		9,562	364	4,601	146	7	6	18	32	1,040	739	2,610
					Region 6, Scandinavia							
Denmark	*	408	0	60	-	-	0	3	-	7	107	232
Sweden	*	253	0	72	-	-	1	69	-	3	0	109
Finland	*	196	0	25	-	-	-	1	-	4	1	166
Norway	*	113	-	-	-	-	-	8	-	2	1	103
Iceland	*	14	-	3	-	-	-	-	-	-	-	11
Total, Region 6		985	0	159	-	-	1	80	-	15	108	620
Percent of total		100	0	16	-	-	0	8	-	2	11	63
					Region 7, North America							
U.S.A.	*	10,436	146	682	-	49	8	-	-	1,108	8,445	-
Canada	*	1,255	20	153	-	188	-	-	-	455	440	-

Table B1. (continued)

	Year	Total N	AS	AN	ASN	AP	SN	CN	CC	U	ON	OC
Total, Region 7		11,691	165	835	-	237	8	-	-	1,562	8,885	-
Percent of total		100	2	7	-	2	0	-	-	13	76	-
Region 8, Central America, Mexico, and the Caribbean												
Mexico	*	1,193	351	55	-	56	-	-	-	433	239	60
Cuba	2	294	83	74	-	-	-	-	-	137	-	-
El Salvador	*	40	30	-	-	-	-	-	-	-	-	10
Nicaragua	*	38	3	2	-	-	-	-	-	29	5	-
Honduras	5	23	2	1	-	1	-	-	-	16	-	4
Jamaica	3	9	5	1	-	0	-	-	-	3	-	0
Trinidad & Tobago	1	5	4	-	-	-	-	-	-	1	-	-
Martinique	2	3	0	0	-	-	-	-	-	2	-	0
Guadelupe	*	3	-	-	-	-	-	-	-	-	-	3
Haiti	*	2	-	-	-	-	-	-	-	-	-	2
Belize	*	1	0	-	-	0	-	-	-	0	-	1
Subtotal		1,611	478	132	-	57	-	-	-	620	244	79
Percent of subtotal		100	30	8	-	4	-	-	-	38	15	5
Guatemala		56	17	4	-	2	-	-	-	21	8	3
Costa Rica		51	15	4	-	2	-	-	-	19	8	3
Dominican Republic		31	9	3	-	1	-	-	-	12	5	2
Panama		12	4	1	-	0	-	-	-	5	2	1
St.Vincent & Granada		3	1	0	-	0	-	-	-	1	0	0
Barbados		2	1	0	-	0	-	-	-	1	0	0
St. Lucia		1	0	0	-	0	-	-	-	1	0	0
Dominica		1	0	0	-	0	-	-	-	0	0	0
St. Christopher-Nevis		1	0	0	-	0	-	-	-	0	0	0
Bahamas		0	0	0	-	0	-	-	-	0	0	-
Bermuda		0	0	0	-	0	-	-	-	0	0	-
Subtotal		157	47	13	-	6	-	-	-	60	24	8
Total, Region 8		1,768	525	145	-	63	-	-	-	680	267	87
Region 9, South America												
Brazil	*	814	157	104	-	100	-	0	0	381	11	61
Colombia	*	181	8	5	-	-	-	-	-	127	-	41
Venezuela	5	123	7	-	-	9	-	-	-	60	-	48
Argentina	*	98	3	3	-	-	-	-	-	68	7	17
Chile	*	86	-	-	-	9	37	-	-	34	-	7
Peru	*	54	3	9	-	2	-	-	-	38	-	1
Ecuador	5	43	0	0	-	8	2	0		34	-	-
Uruguay	8	20	-	0	-	0	3	-	-	9	-	10
Guyana	5	10	5	-	-	-	-	-	-	5	-	-
Surinam	5	10	0	0	-	-	-	-	-	7	-	2
Paraguay	5	1	0	-	-	-	0	-	-	1	-	1
Subtotal		1,440	182	120	-	128	37	1	0	765	19	188
Percent of subtotal		100	13	8	-	9	3	0	0	53	1	13
Bolivia		3	0	0	-	0	0	-	-	1	0	0
French Guiana		0	0	0	-	0	0	-	-	0	0	0
Subtotal		3	0	0	-	0	0	-	-	2	0	0
Total, Region 9		1,443	183	120	-	128	37	1	0	767	19	188

Table B1. (continued)

	Year	Total N	AS	AN	ASN	AP	SN	CN	CC	U	ON	OC
					Region 10, Oceania							
New Zealand	3	40	11	2	-	13	-	0	-	14	1	-
Fiji	*	10	10	-	-	-	-	-	-	-	-	-
Subtotal		50	21	2	-	13	-	0	-	14	1	-
Percent of subtotal		100	42	5	-	25	-	0	-	27	1	-
Australia		320	134	16	-	80	-	-	-	86	3	-
Fr. Polynesia		1	0	0	-	0	-	-	-	0	0	-
New Caledonia		0	0	0	-	0	-	-	-	0	0	-
Tonga		0	0	0	-	0	-	-	-	0	0	-
Subtotal		321	135	16	-	80	-	-	-	87	3	-
Total, Region 10		371	156	18	-	93	-	0	-	100	4	-
					All Regions							
Total, Global		70,505	3,654	17,059	1,467	3,272	52	99	62	28,215	10,431	7,519
Percent of total		100	5	24	0	5	0	0	0	40	15	11

South Africa was not used to calculate the profile for Region 4 (Africa). See text for explanation.

reported partitioning for some year in the 1980s, numbers indicate the proxy year used to partition the 1984-1985 total: 1, 1981-1982; 2, 1982-1983; through to 8, 1988-1989; 9, 1989-1990.

Top portions of regional sections list countries reporting partitioning among fertilizer types for some year in the 1980s. Lower portions of regional sections give fertilizer consumption by type estimated using regional consumption profiles calculated from countries in the top portion.

Fertilizer abbreviations are AS, ammonium sulphate; AN, ammonium nitrate; ASN, ammonium sulphate-nitrate; AP, ammonium phosphate; SN, sodium nitrate; CN, calcium nitrate; CC, calcium cyanamide; U, urea; ON, other nitrogenous fertilizers; and OC, other complex fertilizers.

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